THE STRESS-STRAIN RELATIONSHIP OF A LIGHTWEIGHT CONCRETE

by

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SCHOOL OF GRADUATE STUDIES

The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance, a thesis entitled

THE STRESS-STRAIN RELATIONSHIP OF A

LIGHTWEIGHT CONCRETE

submitted by Sidney Herbert Simmonds, B.Sc.
in partial fulfilment of the requirements for the degree of Master of Science.

PROFESSOR

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A DISSERTATION

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES

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DEPARTMENT OF CIVIL ENGINEERING

by

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ABSTRACT

Concrete cylinders, poured from an expanded shale aggregate concrete, were tested to obtain characteristic stress-strain curves. Variables used included design strength, size of cylinder, type of cure, age at and method of testing.

These tests show that this concrete is capable of carrying appreciable load at strains beyond the ultimate load; as much as 40% of the ultimate load at twice the strain corresponding to this point.

This expanded shale concrete is found to have a marked decreased value (approximately one-half), for the modulus of elasticity compared with the accepted value for standard sand and gravel concrete. However, the limiting strain, based on 85% of the ultimate compressive strength, is similar for both concretes.

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INTRODUCTION

Nature of Subject

The generally accepted theory used to design reinforced concrete structural members is based on the assumption that concrete under compression behaves elastically until a certain strain at which complete failure occurs. The limitations of this assumption are of no serious consequence for structural members designed by the straight line or elastic theory. However, if members are to be designed by ultimate or plastic theories, a more complete knowledge of the stress-strain curve for concrete is required. Similarly, the theory used to predict the ultimate carrying capacity of a concrete structural member, or determine the actual stress distribution corresponding to excessive strains, say above 0.2%, must be based on stress-strain relationships past the point of failure. Even if there is no intention of loading a structure to its ultimate load, or to produce excessive strains, a thorough knowledge of the stress-strain curve into the plastic region is essential to properly determine factors of safety and thus allow more economical designs.

The straight line or elastic theory is based on the observation that concrete specimens, subjected to compressive stresses in the standard reaction type testing machine, approximately obey Hooke's Law until

about 90% of the ultimate compressive strength, then flow plastically to a limiting strain after which all load carrying capacity is lost.

Numerous investigators [1, 2, 3], found, however, that with care, concrete could be made to carry load at strains well beyond the apparent breaking strain. They explained the apparent instantaneous inability to carry load in terms of a sudden release of elastic energy stored in the uprights of the testing machine which strained the specimen so rapidly that the gradual decrease in load was not noticed. Ramaley and McHenry [1] demonstrated that by enclosing the test concrete cylinder with a stiff disc spring that reacted against the elastic energy in the testing machine, they could strain the cylinder well into the plastic range and still have it carry load. In this investigation, with a lightweight aggregate concrete, cylinders were found to carry as much as 40% of the ultimate loads at strains twice that corresponding to this point.

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[1] Ramaley D. and McHenry D. "Stress-Strain Curves for Concrete Strained beyond the Ultimate Load." Lab. Report SP-12, U.S. Bureau of Reclamation.

[2] Hognestad E. "A Study of Combined Bending and Axial Load in Reinforced Concrete Members." U. of Illinois, Bulletin 399.

[3] Evans, R.H. "The Plastic Theories for the Ultimate Strength of Reinforced Concrete Beams." Journal Institution of Civil Engineers. Vol. 21, 1943.

Historical Review

Earliest investigators in the field of "Strength of Materials", by necessity attempted to evolve empirical design techniques from their observations. At the beginning, concrete technology proved to be no exception and experimental inelastic theories were developed. However, acceptance of Navier's theory of bending, based on Bernoulli's assumption regarding plane sections remaining plane and Hooke's Law was wide-spread. In 1894 the Coignet-Tédesco theory, based on Navier's bending theory, was proposed, assuming a linear stress distribution in the concrete. This theory was sufficiently accurate for most designs and because of its mathematical simplicity was universally adopted for the straight line or standard theory which was responsible for the rapid development of concrete structural design at the beginning of this century. So wide-spread was the acceptance of this theory that its approximate character was forgotten and it was applied to cases where it was not valid.

In 1921, McMillan [4] made a study of column test data and showed that in structural reinforced concrete columns the stresses in the steel could exceed, due to plastic action of the concrete, the stresses predicted by the standard theory. This led to the A.C.I. column

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[4] McMillan, F.R. "A Study of Column Test Data." Proceedings American Concrete Institute. Vol. 17, 1921, pp. 150 - 171.

investigations in the 1930's by Lyse, Slater, and Richart. From these investigations the A.C.I. Building Code was changed such that columns were designed by plastic considerations.

In 1931, Emperger [5] wrote a paper on the modular ratio and the allowable stresses. From this paper a number of ultimate or plastic design theories originated. In the U.S.S.R. and Brazil especially a definite trend to plastic design has occurred. Several North American Codes, including the A.C.I. building code, are in the process of changing at this time.

So far, most of this work has been done with standard sand and gravel concretes. This investigation was to determine the similarities and differences in the stress-strain relationship over the entire range for an expanded shale concrete compared with standard concrete and to show what effect these differences may have in the design of lightweight concrete structures.

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[5] A summary of this and other papers about early investigations are found in the thesis "A Study of Combined Bending and Axial Load in Reinforced Concrete Members" by Hognestad. U. of I. Bulletin 399.

Chapter 1

Scope of Testing Programme

The primary intention of this investigation is to show the shape of the stress-strain curve for concrete, made with expanded shale aggregate, throughout the complete range of strain and to determine whether this general pattern is affected by such factors as size, strength, age, type of cure and method of testing.

In order to give a range of strengths, mixes were designed to give 28 day compressive strengths of 2500, 3000, 3500, 4000, 4500, and 5000 psi. Twelve 3" x 6" cylinders were cast from each pour and were broken in the following sequence: 2 at 3 days, 3 at 7 days, 4 at 28 days and 3 at 42 days. These cylinders were all cured in a standard moist room after 24 hours in the forms with the exception of one cylinder from each of the tests at 7, 28, and 42 days. With these cylinders the cure was varied by removing them from the moist room on the date of the next earlier test. (i.e. one of the 7 day test cylinders was removed from the moist room on the day of the 3 day tests, one of the 28 day test cylinders was removed from the moist room on the day of the 7 day tests, etc.). These cylinders were all tested without the use of any restraining device. The above tests were duplicated with cylinders being loaded when enclosed by the restraining springs similar to those developed by Ramaley and McHenry.

In addition, two 6" x 12" cylinders were cast from each of the original mixes in an attempt to determine whether a size factor exists. These cylinders were tested without the use of the restraining springs, because of the limiting capacity of the testing machine.

An attempt was also made to determine whether steam-curing had any effect on the stress-strain relationship. Twelve 3" x 6" cylinders were cast from each mix with design strengths of 2500, 3000, 4000, and 5000 psi. concrete. Since the results of the above tests were in close agreement, it was deemed satisfactory to test these cylinders without the use of the restraining springs. All cylinders in this group were removed from the forms after 24 hours and broken in the sequence shown in table 1.

TABLE 1

Sequence of Steam-Cured Tests

No. of cylinders for each strength	Length of type of cure in days					Age at test days
	Forms	Moist before steam	Steam	Moist after steam	Air	
2	1	--	1	--	--	2
2	1	--	1	5	--	7
2	1	--	1	26	--	28
2	1	2	1	24	--	28
2	1	--	1	--	26	28
2	1	27	--	--	--	28

Chapter 2

Mix: Materials, Proportions and Techniques

Materials

The aggregate used throughout this investigation was an expanded shale, known commercially as "Herculite", manufactured by Light Weight Aggregates of Canada, Ltd., Calgary. Standard Type I Portland Cement was used and the mixing water was obtained directly from the City of Edmonton water mains.

The following physical properties of the aggregate are included in this report, not with the intention of presenting a complete description of its properties, but rather as an aid to subsequent investigators in identifying this aggregate, if comparisons of similar test data on different types of aggregates were to be made. For this reason, absorption and specific gravity are not recorded as they were found to vary with the length of time of determination, size fraction, etc.; and although they influenced the mix procedure, did not directly affect the mix proportions.

Since one of the characteristics of this aggregate is to segregate excessively under normal handling, it is divided into the following three size fractions, fines (pan to 3/16") intermediate (3/16" to 3/8") and coarse (3/8" to 3/4").

The unit weights given in table 2 are for the bin dry condition as it was felt this was the only practical basis on which to select proportions.

TABLE 2

Bin Unit Weights

Trial	Coarse	Intermediate	Fine
1	42.2 #/cu.ft.	46.5 #/cu.ft.	73.0 #/cu.ft.
2	42.5	46.8	73.0
3	42.5	46.9	73.1

TABLE 3

Sieve Analysis

Sieve size	Coarse % retained	Intermediate % retained	Fine % retained	Fine Cum.% Ret.
3/4	0.6	--	--	--
1/2	36.5	--	--	--
3/8	35.8	--	--	--
#3	27.1	53.4	--	--
#4	--	38.3	0.2	0.2
#8	--	8.3	7.5	7.7
#16	--	--	18.2	25.9
#30	--	--	26.2	52.1
#50	--	--	20.2	72.3
#100	--	--	13.6	85.9
#200	--	--	11.3	244.1
pan	--	--	2.8	

Finess Modulus = 2.44

The colour test for organic impurities gave an index of #1 and the % passing a #200 sieve was found to be 2.85%.

PROPORTIONS:

Proportions for the mixes used during this investigation were selected on the recommendations outlined in the A.C.I. Journal, September, 1954. The design tables from this report and a detailed mix design are included in Appendix I. Since the quantity of coarse aggregate tabulated in the design tables includes both the intermediate and coarse fractions of this lightweight aggregate, these fractions were split 60% coarse and 40% intermediate on the recommendations of L. R. Lauer [6]. A summary of the proportions used in the various batchings is given in table 4.

Table 4

Design Proportions by Weight for Expanded Shale Concrete Based on 1 Cu. Yard, All Weights in Lbs.

Designed 28 day compressive straight psi.	2500	3000	3500	4000	4500	5000
Cement	480	530	585	640	700	770
Water *	340	340	340	340	340	340
Fines	1040	1000	970	935	900	855
Intermediate	315	315	315	315	315	315
Coarse	460	460	460	460	460	460

* Note - This is the theoretical water required for mixing to produce a 3" slump and does not include water that is absorbed by the aggregate.

6 Lauer, L.R. "Some Properties of Lightweight Aggregates". Master's Thesis, U. of A. 1955.

Because of the small quantities of material involved, all mixing was done by hand, using a trowel and mixing trough (see photograph 1).

Photograph 1 - Preparation for a Typical Mix

Mixing Techniques

Due to the excessive absorptive character of the aggregate, it is not practical to combine the materials in the conventional manner if the aggregate were in the bin-dry condition. As it is impossible to accurately predict the quantity of water involved, the following technique was used.

Approximately 24 hours before the time of mixing, the required weight of aggregate, determined in the bin-dry condition, was immersed in water. Immediately before batching the aggregate was drained and mixed thoroughly with the cement. Water was then added until the desired slump was obtained. After 24 hours of pre-soaking, the rate of absorption is decreased to the extent that no noticeable effect to the consistency of the mix is observed before the time of initial set.

Compaction procedure for the smaller cylinders was similar to standard practice, except that a 5/16" diameter rod was selected for tamping as it gives the same proportion of tamping rod area to total cylinder area.

Chapter 3

Apparatus

The apparatus devised by Ramaley and McHenry [7] was duplicated for testing 3" x 6" cylinders. A brief description of this apparatus follows:

When the cylinders were loaded without restraint the stress applied could be determined directly from the load registered by the testing machine.

To evaluate the strain an extensometer was used, shown in photograph 2, that could be fastened directly to the concrete cylinder by two pointed set screws placed opposite each other in each end ring. These rings are connected by two spring-brass strips 5 inches long, placed diametrically apart.

The two brass strips were slightly bowed such that they could readily deflect like bow springs in proportion to the relative movement of the two end rings. "SR-4" type wire resistant strain gauges were attached both inside and outside of each strip to measure the flexural strains in the strips. The outside or tension gauges were connected to form a series circuit so that registered resistances would be larger than for single gauges. Similarily, the inside or compression gauges were also connected in series. Since

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7 Ramaley D. and McHenry D. "Stress-Strain Curves for Concrete Strained beyond the Ultimate Load."
Lab. Report SP-12, U.S. Bureau of Reclamation.

the strain registered by the "SR-4" gauges was the bending in the brass strips rather than the true strains in the concrete, it was necessary to calibrate the instrument.

The extensometer was calibrated by placing it upon a 3" x 6" cylinder of plastic material having large compressibility. Two dial gauges were placed between the loading head and the loading platform to measure their relative movement and thus the relative displacement of the two end rings could be determined by simple proportion. As the cylinder was loaded in the testing machine simultaneous readings were taken with the "SR-4" gauges and the two dial gauges. A curve was then plotted (see figure 3) that shows the strain in the cylinder as a function of the readings of the "SR-4" gauges. Calibrations were run after each 25 to 30 cylinders.

The dimensions of the disc springs used for restrained loading were originally chosen such that a load of 50,000 pounds would cause a total deflection of 0.057 inches.[8] In order to adapt these discs to testing lightweight aggregate it was found by experience that an initial load of from 15,000 to 20,000 pounds was required if a proper transfer of load was to occur at the ultimate load of the cylinder.

A seamless steel tube fills in the space between the springs and the loading head of the testing machine.

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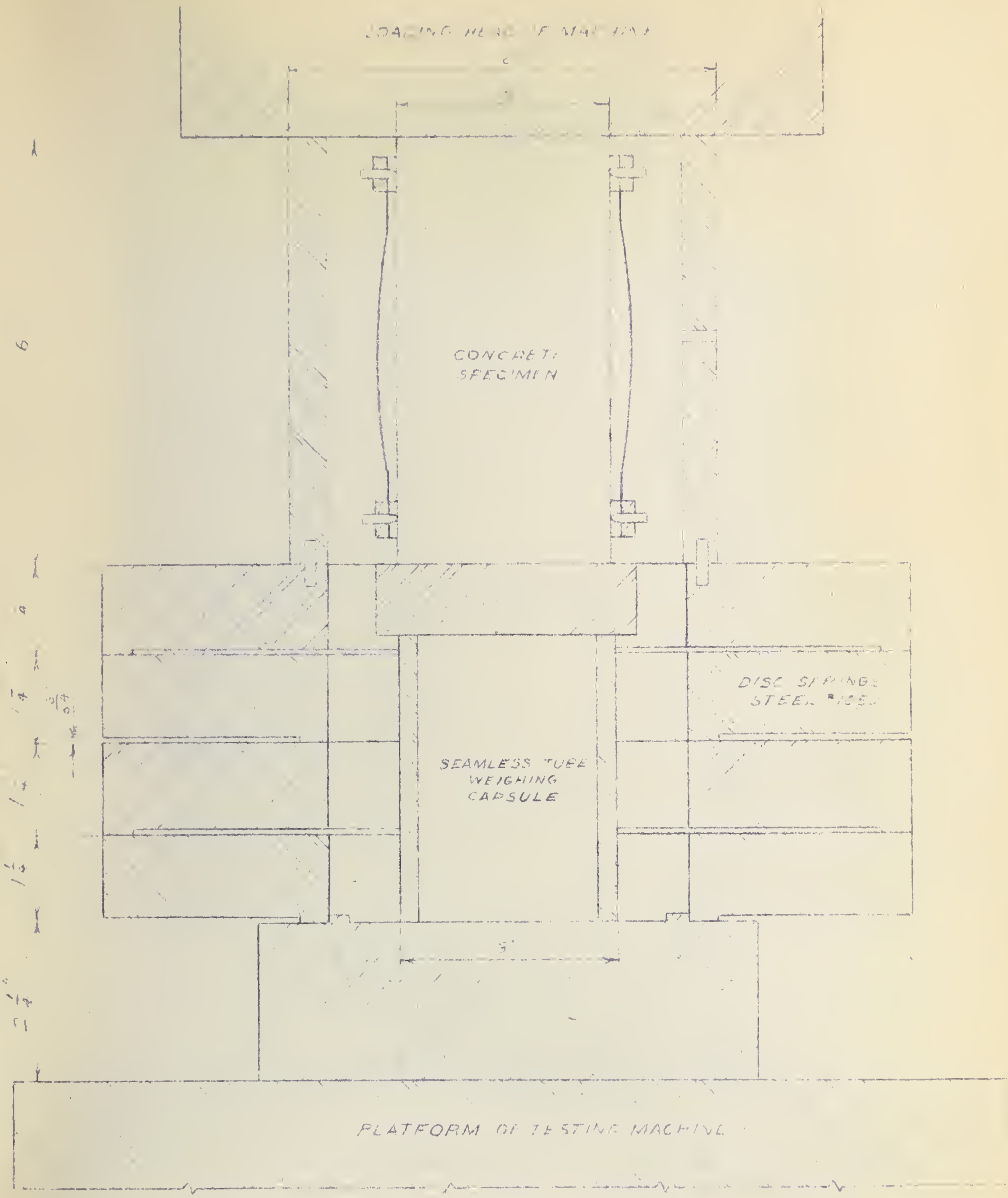
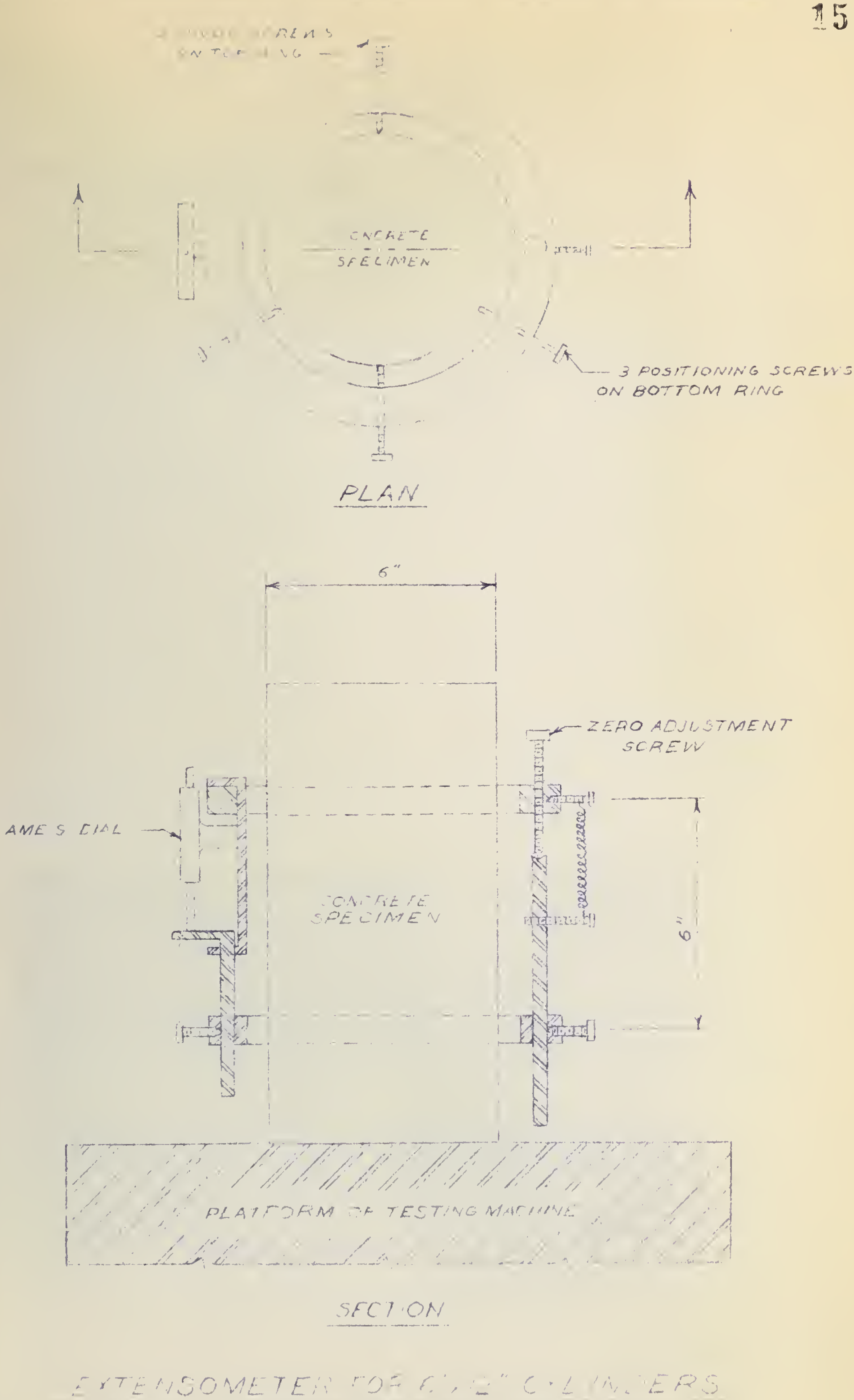
8 Ramaley D. and McHenry D. "Stress-Strain Curves for Concrete Strained beyond the Ultimate Load". Lab. Report SP-12, U.S. Bureau of Reclamation.



DISC SPRING LOADING APPARATUS

FIGURE I



EXTENSOMETER FOR 6 x 12" CYLINDERS

FIGURE 2

In order to have the top of the concrete cylinder flush with the steel tube, the cylinder was capped in place with a Plaster of Paris cap.

In loading specimens enclosed by the disc springs part of the total load is taken by the concrete and part by the springs making it necessary to use a type of weighing capsule to measure the load carried by the concrete. It was found impossible to obtain a consistent calibration with the arrangement used in the original apparatus and, therefore, a $3\frac{1}{2}$ inches O.D. seamless steel tube having a $\frac{1}{4}$ inch wall thickness and a 4 inch length was substituted. (See figure 1). To measure strains in the tube, four strain gauges were placed 90° apart around the outside and connected in series. A 1" thick steel disc was placed above this tube to transfer the load on the concrete to the tube. (See photograph 6).

Photograph 2 - Small Cylinders Enclosed by Extensometer

FIGURE 3

CALIBRATION - EXTENSOMETER

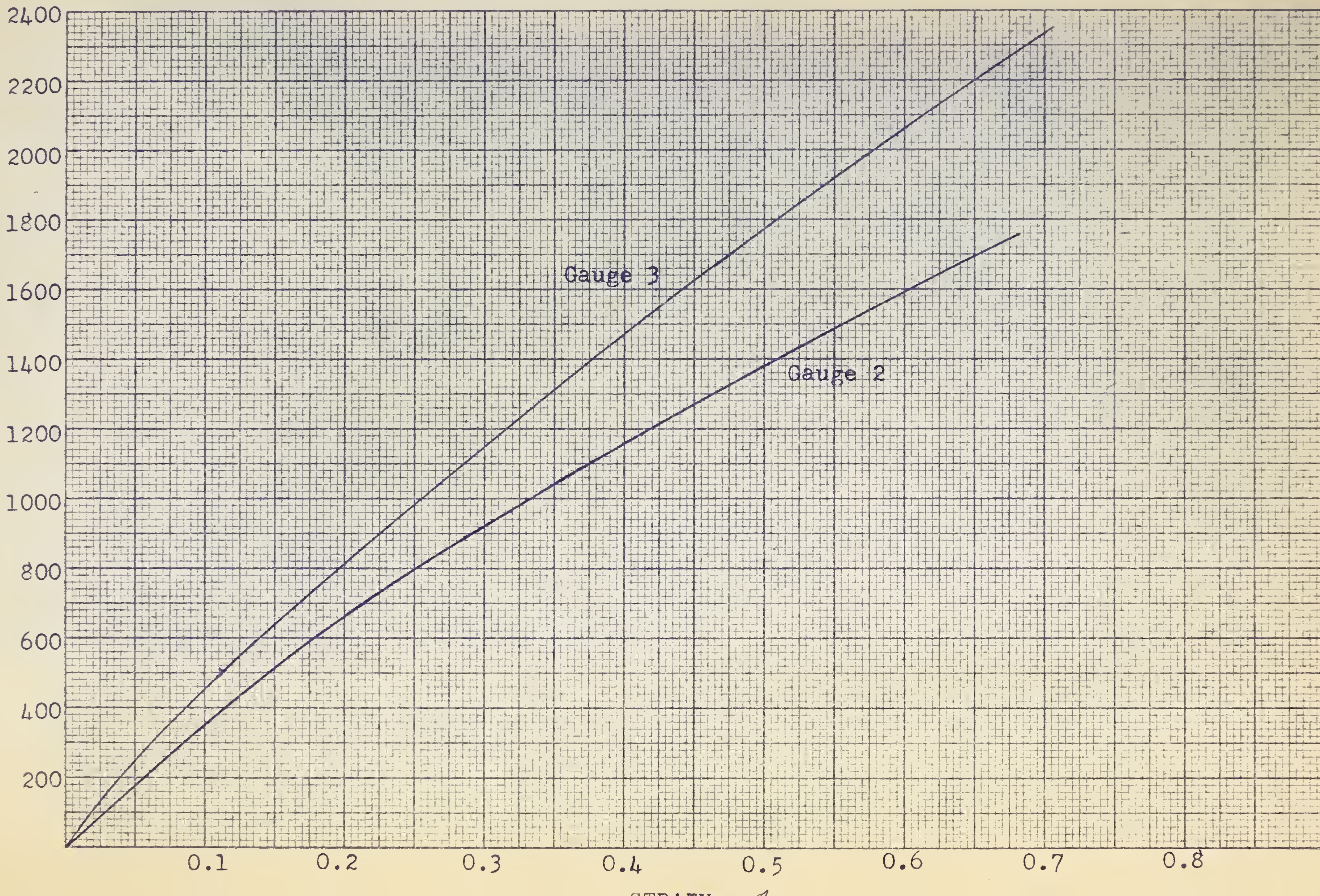
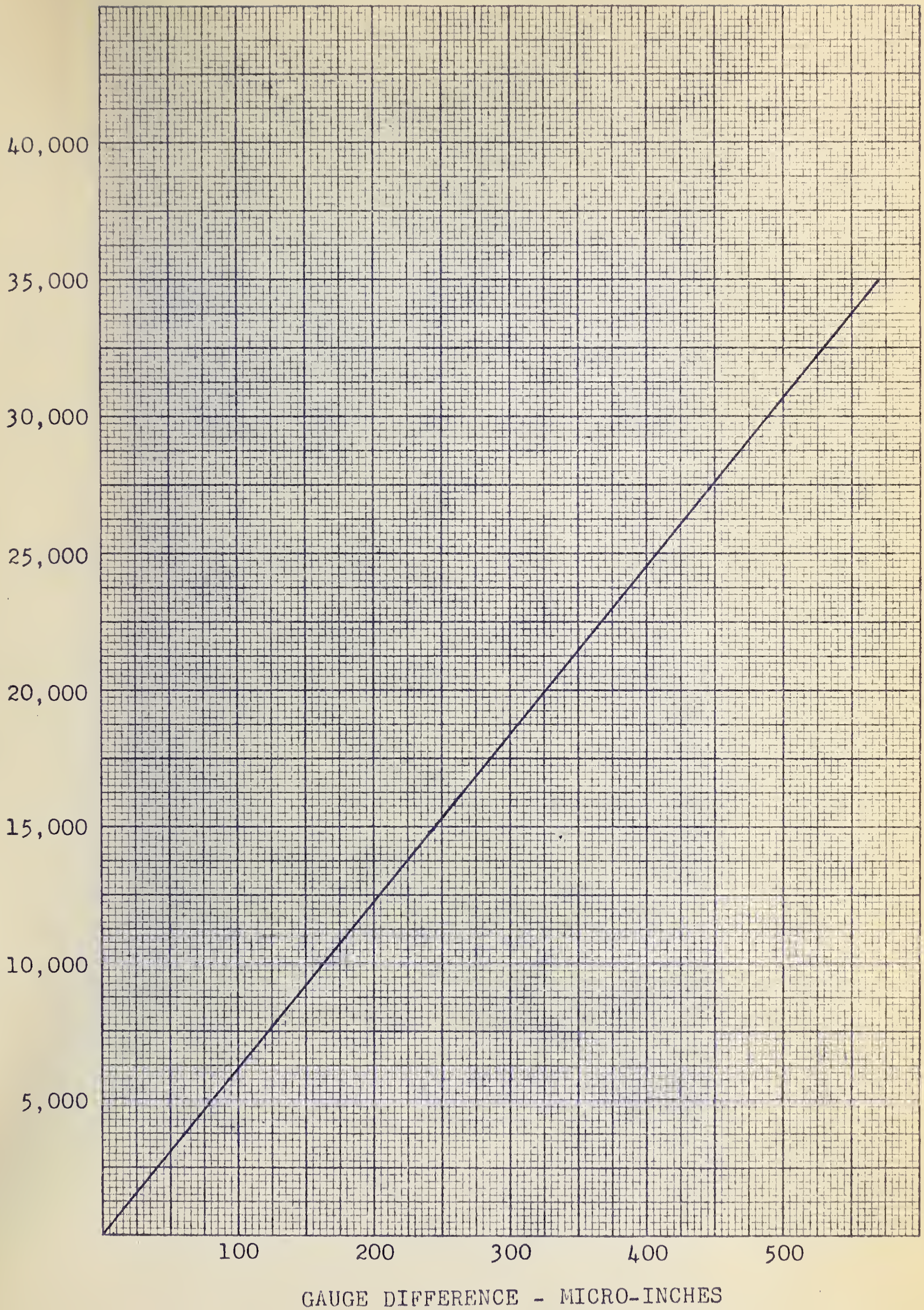
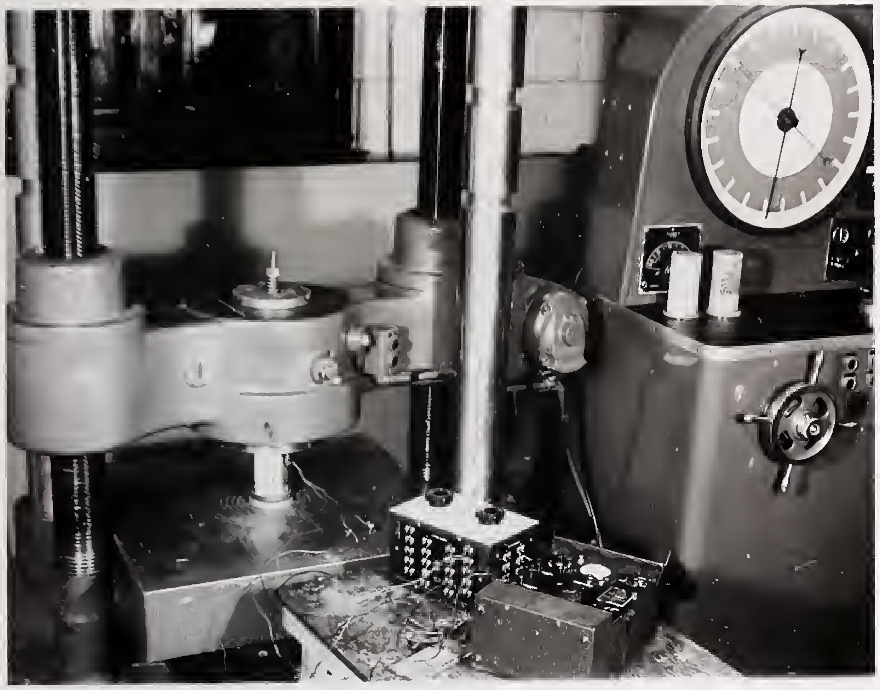


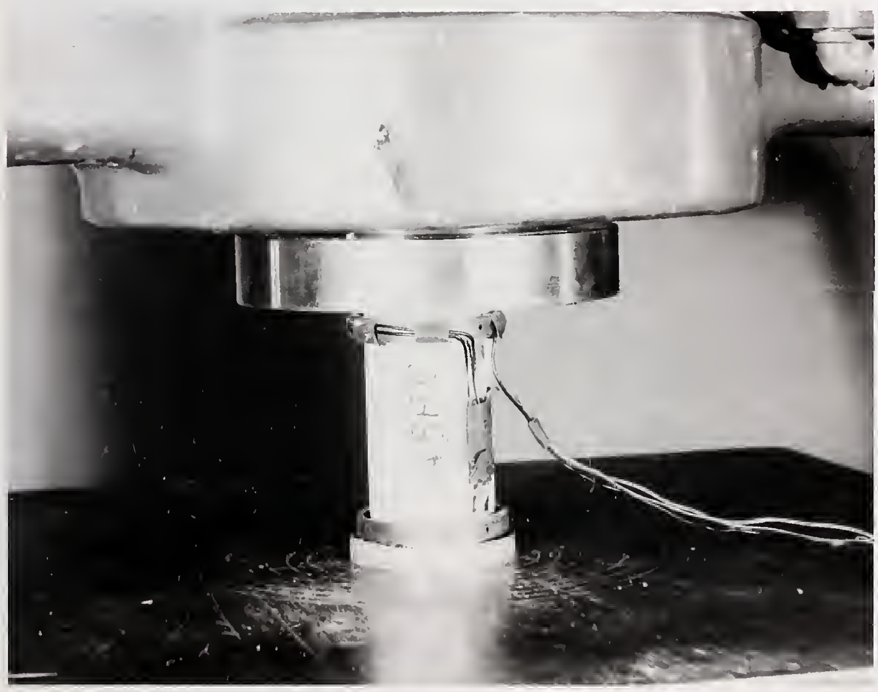
FIGURE 3a.

CALIBRATION - LOAD CAPSULE

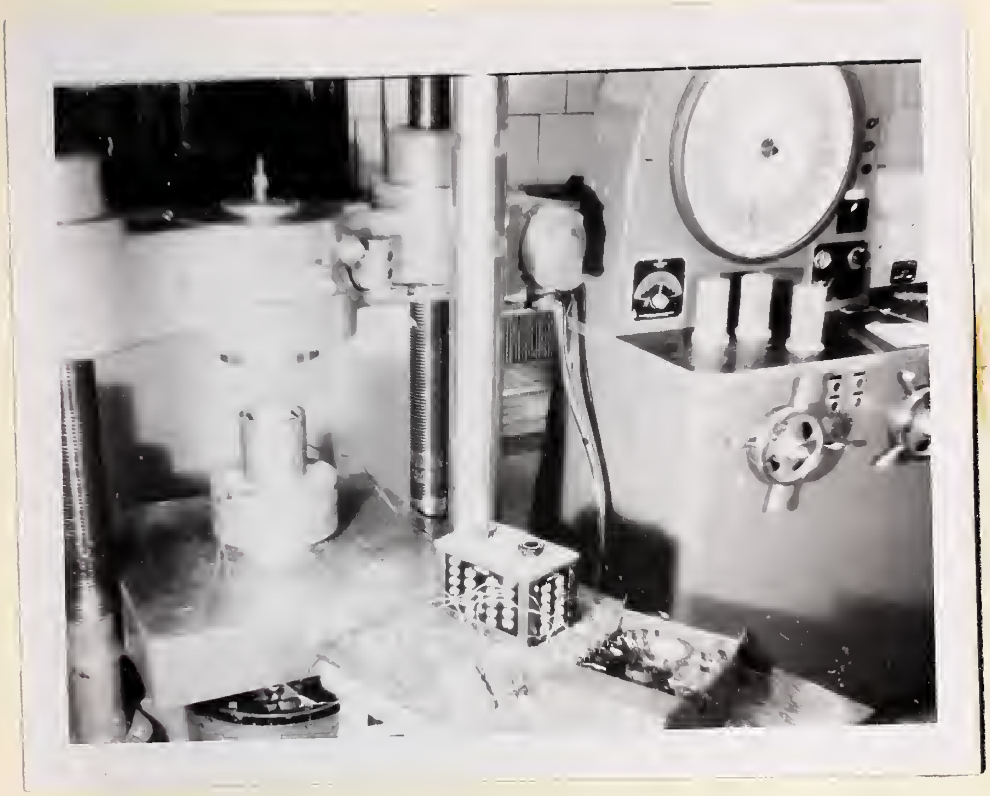




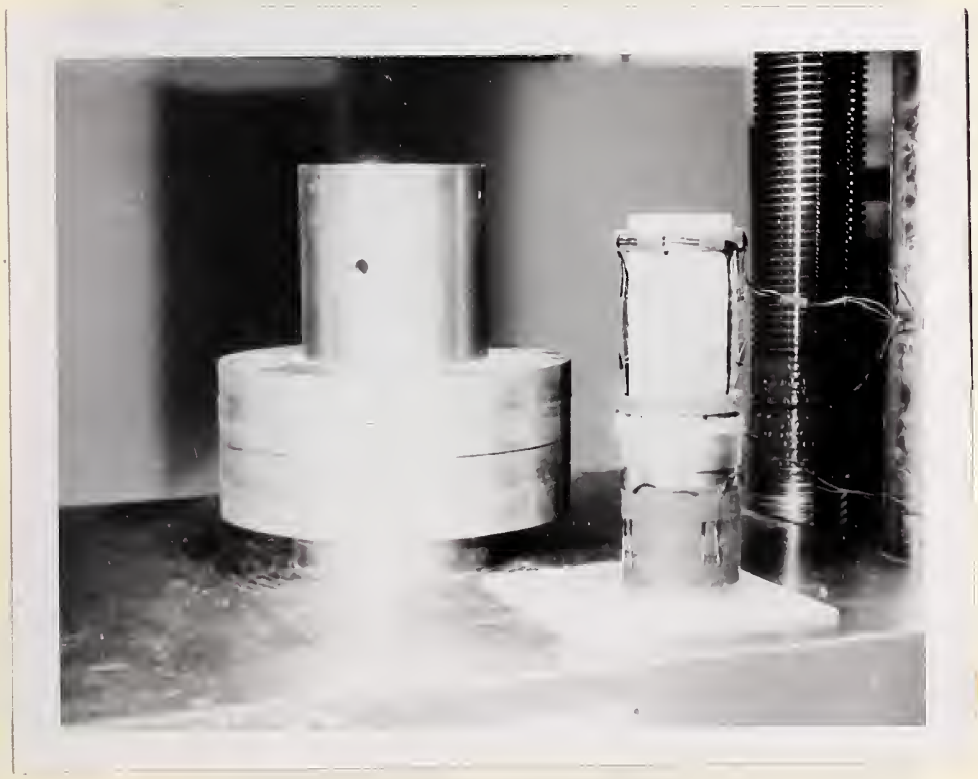
Photograph 3 - General Arrangement of
Testing Machine and Strain Recording Apparatus



Photograph 4 - Cylinder in Place
in Testing Machine



Photograph 5 - General Testing Area
Showing Restraining Springs in Position for Test



Photograph 6 - Restraining Springs
with Weighing Capsule, Disc and Cylinder

This form of weighing capsule was calibrated by placing it in a testing machine and determining the resistance change in the "SR-4" gauges corresponding to the applied load. This arrangement could be calibrated to give an agreement of results within 1 per cent. (See figure 3a).

The larger 6" x 12" cylinders, due to limiations on the range of the testing machine, were tested without the use of any restraining device. Therefore, the applied loads could again be obtained directly from the dial of the testing machine. For determining corresponding strains an extensometer similar to that for the smaller cylinders was used. (See figure 2 and photograph 7).

Photograph 7 - Extensometer for 6" x 12" Cylinders

It consisted of a bottom ring fastened rigidly to the cylinder by means of three pointed set screws placed 120° apart. The top ring was held by two set screws placed opposite each other such that it could rotate about an axis coincident with a diameter. One edge of the ring was held by an adjustable set screw while the other had attached an Ames dial. The dial thus registered strains that were approximately twice the corresponding strains in the concrete cylinder.

Photograph 8 - Constant Temperature Bath
for Steam-curing Cylinders.

Steam-curing in this report, refers to cylinders being immersed in water at an elevated temperature, in this instance 135° F. The apparatus consisted of a stainless steel, constant temperature bath equipped with a thermostatic control capable of holding the temperature to within 1° F. and a mechanical agitator to ensure a uniform distribution of temperature. (See photograph 8).

The testing machine used throughout this investigation was a Baldwin (Southwark-Tate-Emery) hydraulic testing machine having a capacity of 200,000 lbs.

Chapter 4

Notation

The following notation was used throughout this investigation:

For designed compressive strength at 28 days.

1 -- 2500 psi.
2 -- 3000 psi.
3 -- 3500 psi.
4 -- 4000 psi.
5 -- 4500 psi.
6 -- 5000 psi.

For age of specimen at test.

A -- 3 days
B -- 7 days
C -- 28 days
D -- 42 days
E -- 2 days

R - preceding all other symbols indicates cylinder was loaded with restraining springs.

A - following all other symbols indicates cylinder was air-cured.

L - preceding all others indicates a 6" x 12" cylinder.

For example, a cylinder cast from a 3,000 psi. mix, placed in the moist room until 7 days, then removed and allowed to cure in air until tested at 28 days without the restraining springs is denoted as 2CA. Similarly, a cylinder marked R4D signifies it was cast from a 4000 psi. mix, and was moist cured until tested at 42 days with the use of the restraining springs.

The notation for the steam-cured tests is given in table 5.

TABLE 5

Notation for Steam-Cured Tests

	Length of type of cure in days					Age
Notation*	Forms	Moist before steam	Steam	Moist after steam	Air	at test days
SE	1	--	1	--	--	2
SMB	1	--	1	5	--	7
SMC	1	--	1	26	--	28
MSC	1	2	1	24	--	28
SRC	1	--	1	--	26	28
MC	1	27	--	--	--	28

* Number preceding indicates design strength.

Chapter 5

Discussion of Tests

This investigation was divided into three main groups, (1) cylinders cured in standard moist room and loaded without restraint, (2) cylinders cured in standard moist room and loaded with the restraint and (3) cylinders subjected to steam-curing and loaded without restraint.

The first group consisted of 72 - 3" x 6" cylinders and 12 - 6" x 12" cylinders. Although the rate of loading was not accurately determined for each case, the average time for testing a specimen was about twenty minutes.

Stress-strain curves for some of the cylinders in this group are found in figures (4 - 9) (16) and (22). It should be noted, in general, these curves express an almost linear relationship until about 90% of the ultimate strength. After reaching the ultimate strength the concrete undergoes considerable plastic deformation and the load carrying capacity drops.

For the higher strength cylinders, particularly the 6" x 12" size, the fact that they seem to shatter or lose their load carrying capacity soon after passing the ultimate load can be attributed to the sudden elastic recovery in the uprights of the testing machine. In many instances, again particularly with the larger cylinders, the stress was noted to drop gradually as the concrete strained but the rates were sufficiently fast to prevent

accurate readings of the dials and/or gauges.

It was noted that variations occurred between cylinders that presumably were cured and tested under similar conditions. Similarly, small irregularities were present in the curve for an individual cylinder, especially at higher strains. It was felt, however, that these variations and irregularities were primarily due to the arrangement of the aggregate particles. This was based on the observation that agreement in all cases was good through the linear range and the variations became apparent as the concrete began to strain plastically.

The modulus of elasticity reported herein is based on the slope of the secant to the curve passing through the origin and a point corresponding to 45% of the compressive strength. This value was chosen as it represents the allowable flexural stress as given by the current A.C.I. Building Code. The modulus of elasticity can be expressed linearly in terms of the compressive strength for specimens having a compressive strength above 2000 psi. The cylinders having strengths below this value are primarily those tested at 3 days. Since commercial concretes have strengths above this range, it was considered valid to use the linear relationship. For this group of tests (see figure 23) the modulus of elasticity can be expressed as follows:

$$E_c = 880{,}000 + 238\, f'c$$

FIGURE 4

2500 p.s.i. - WITHOUT RESTRAINT

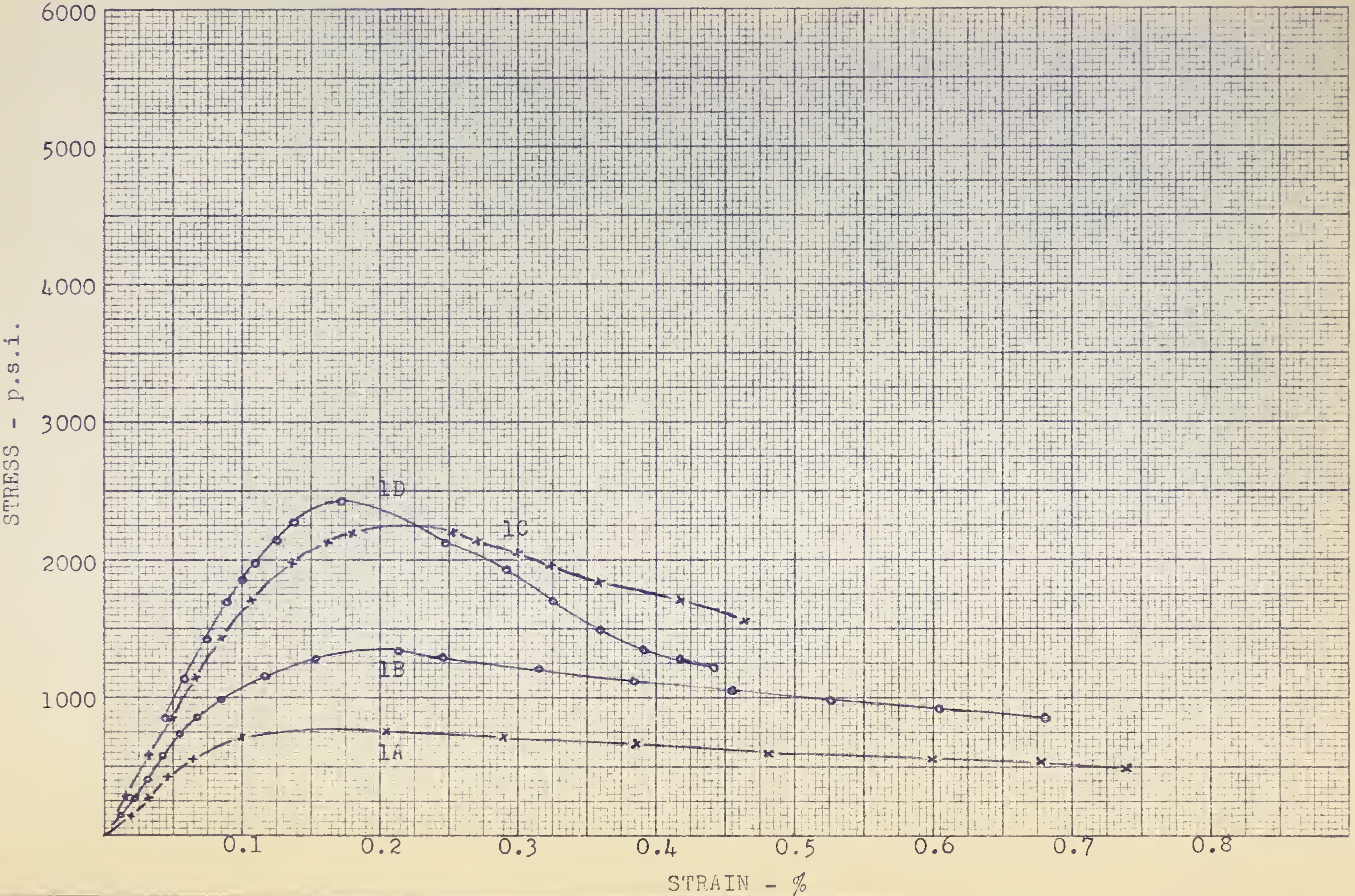


FIGURE 5

3000 p.s.i. - WITHOUT RESTRAINT

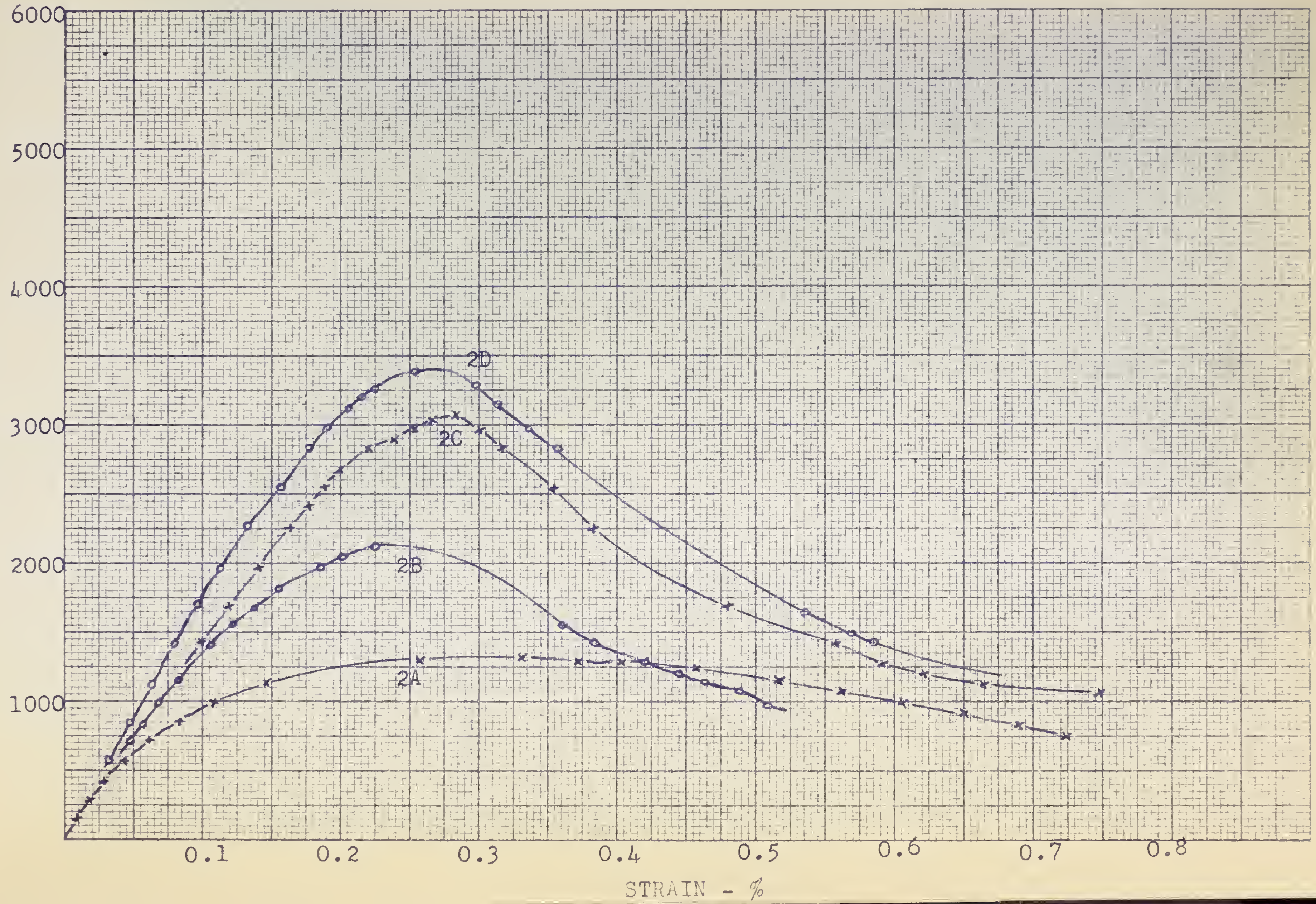


FIGURE 6

3500 p.s.i. - WITHOUT RESTRAINT

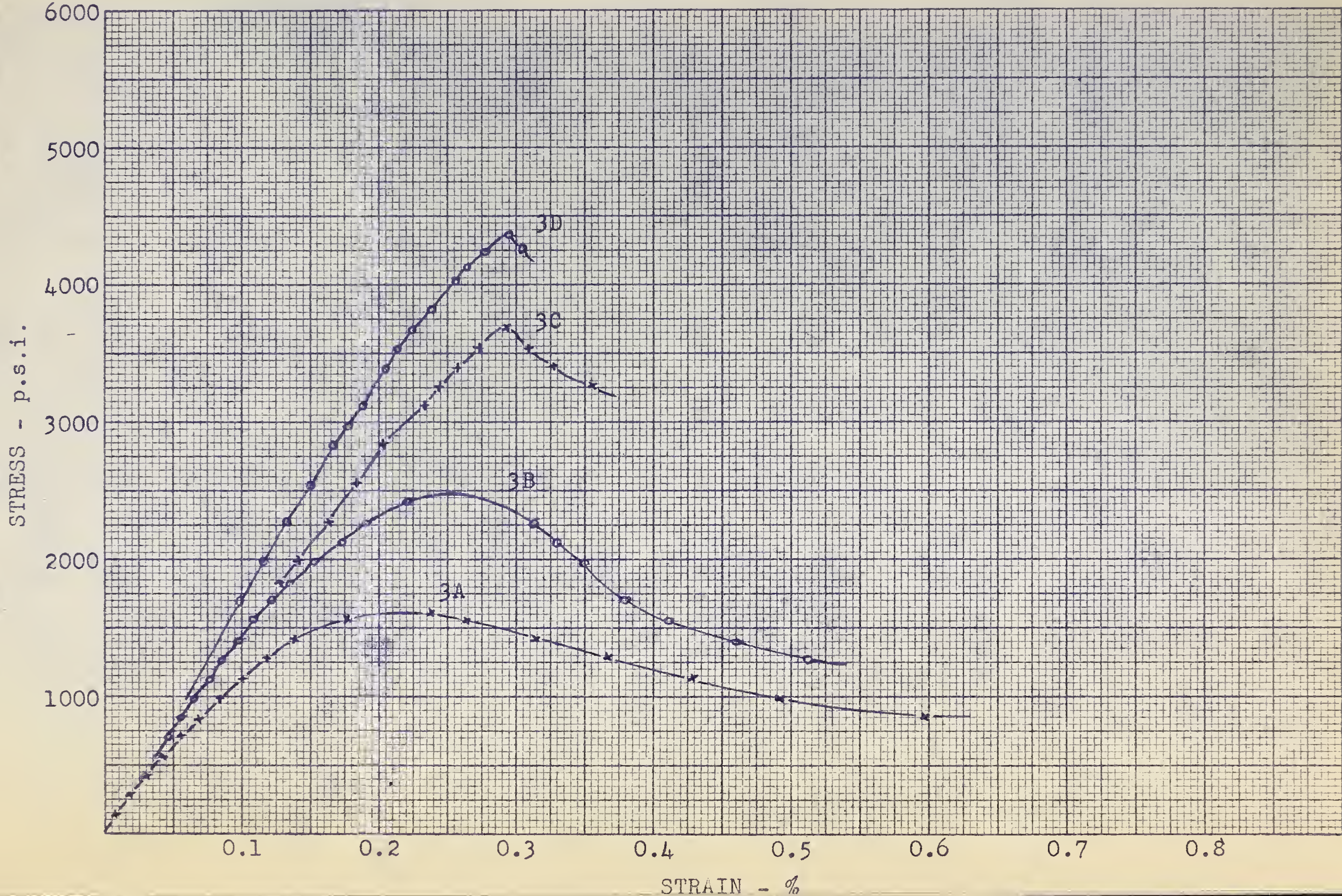


FIGURE 7

4000 p.s.i. - WITHOUT RESTRAINT

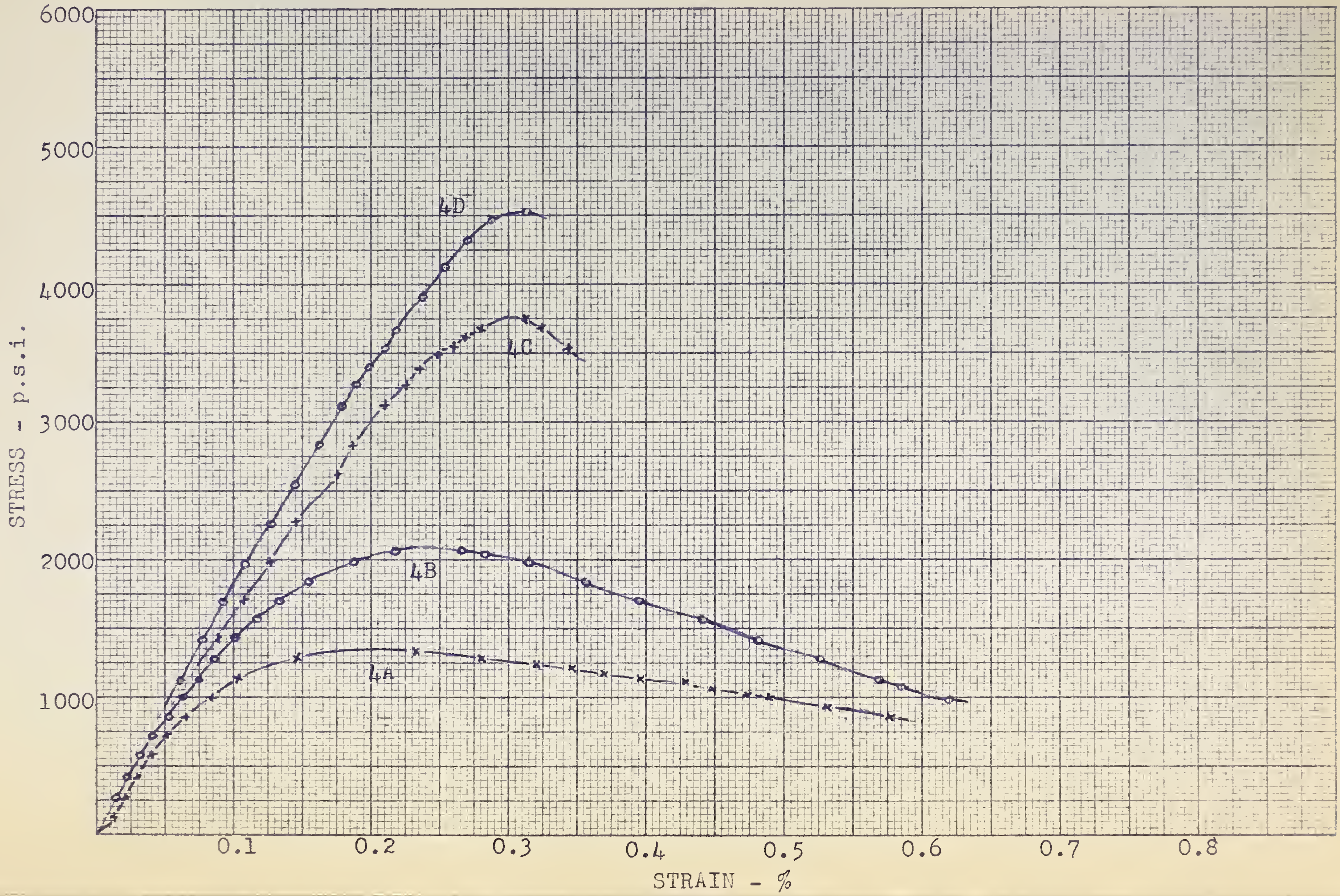


FIGURE 8

4500 p.s.i. - WITHOUT RESTRAINT

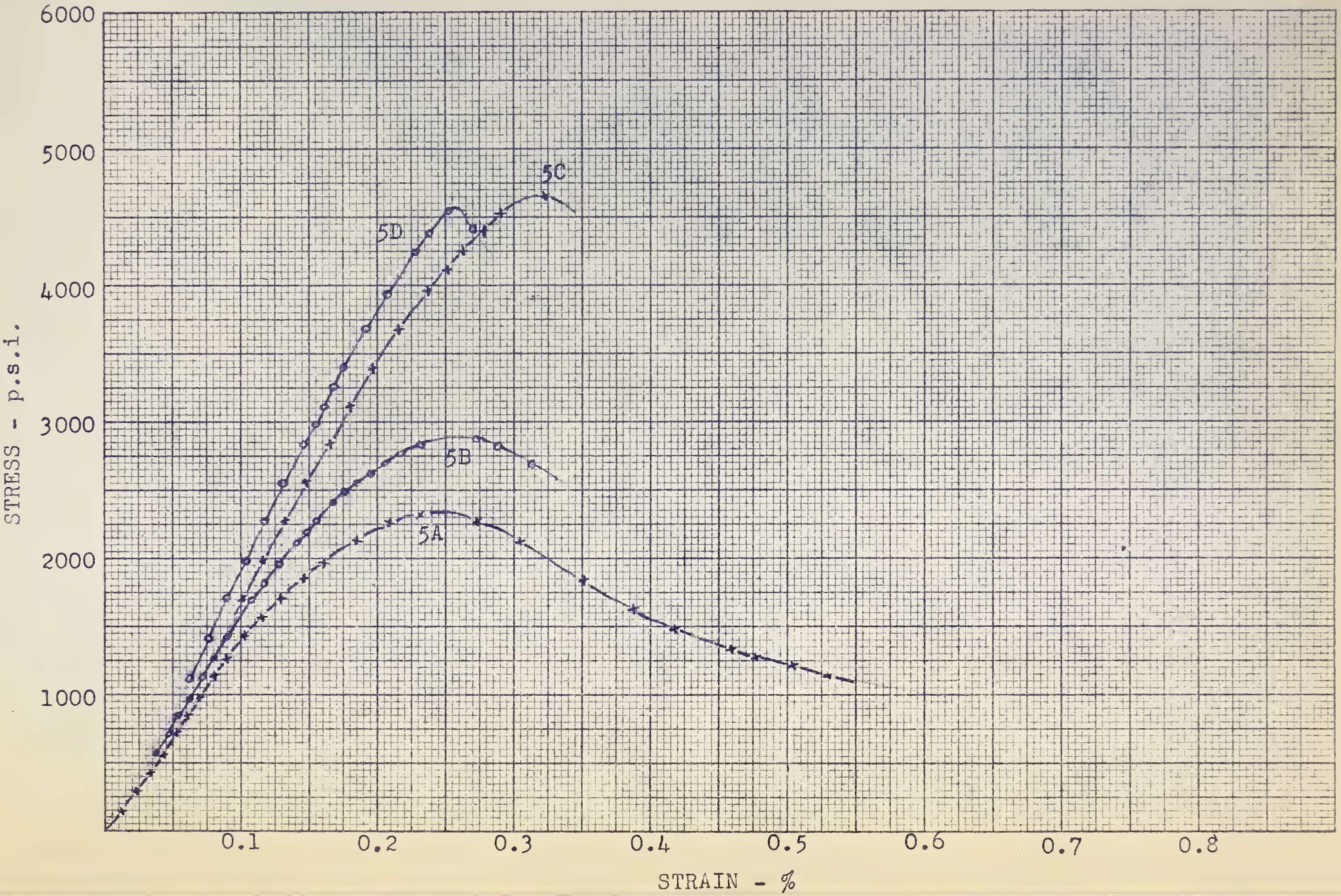


FIGURE 9

5000 p.s.i. - WITHOUT RESTRAINT

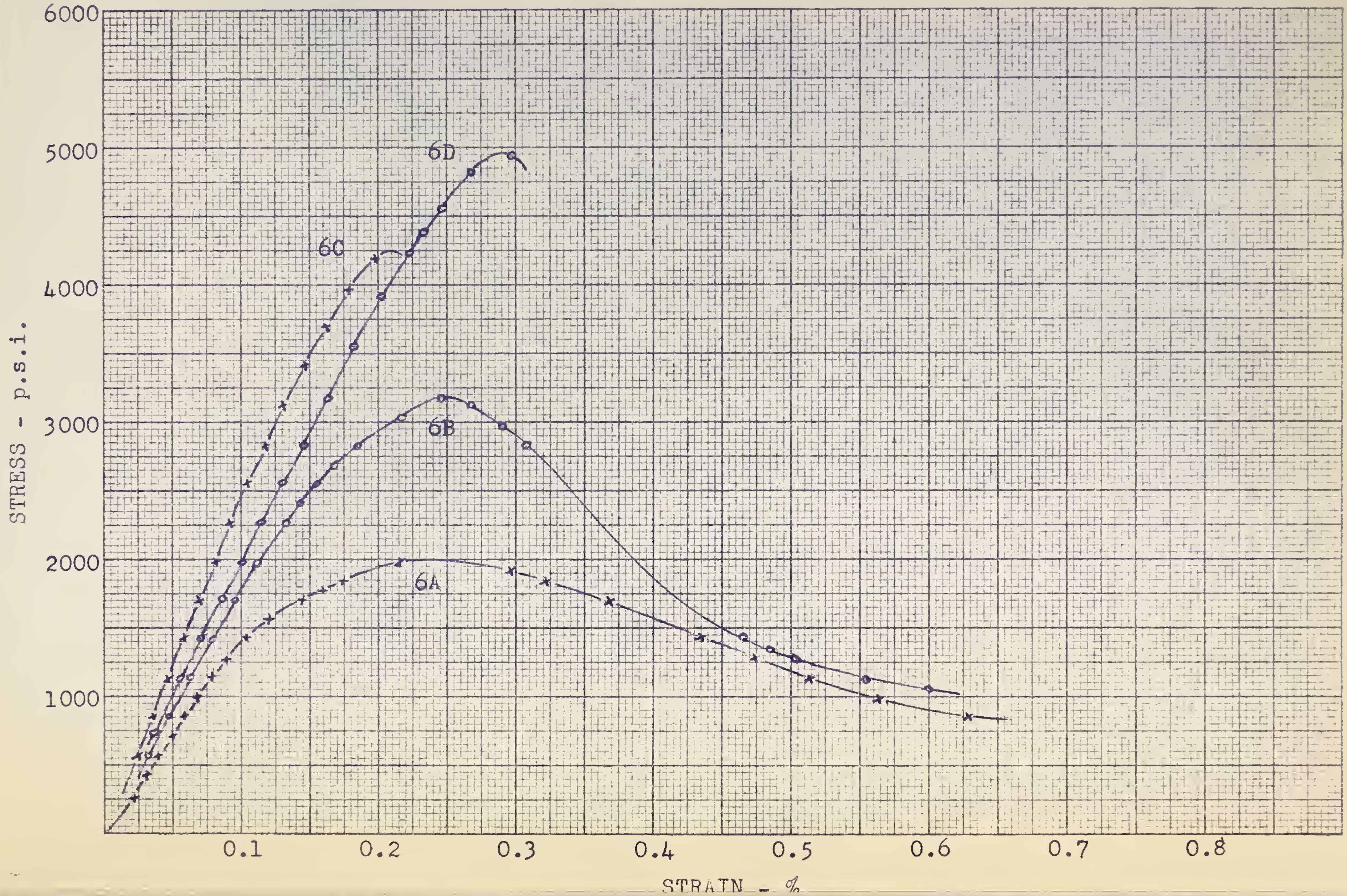


FIGURE 10

2500 p.s.i. - WITH RESTRAINT

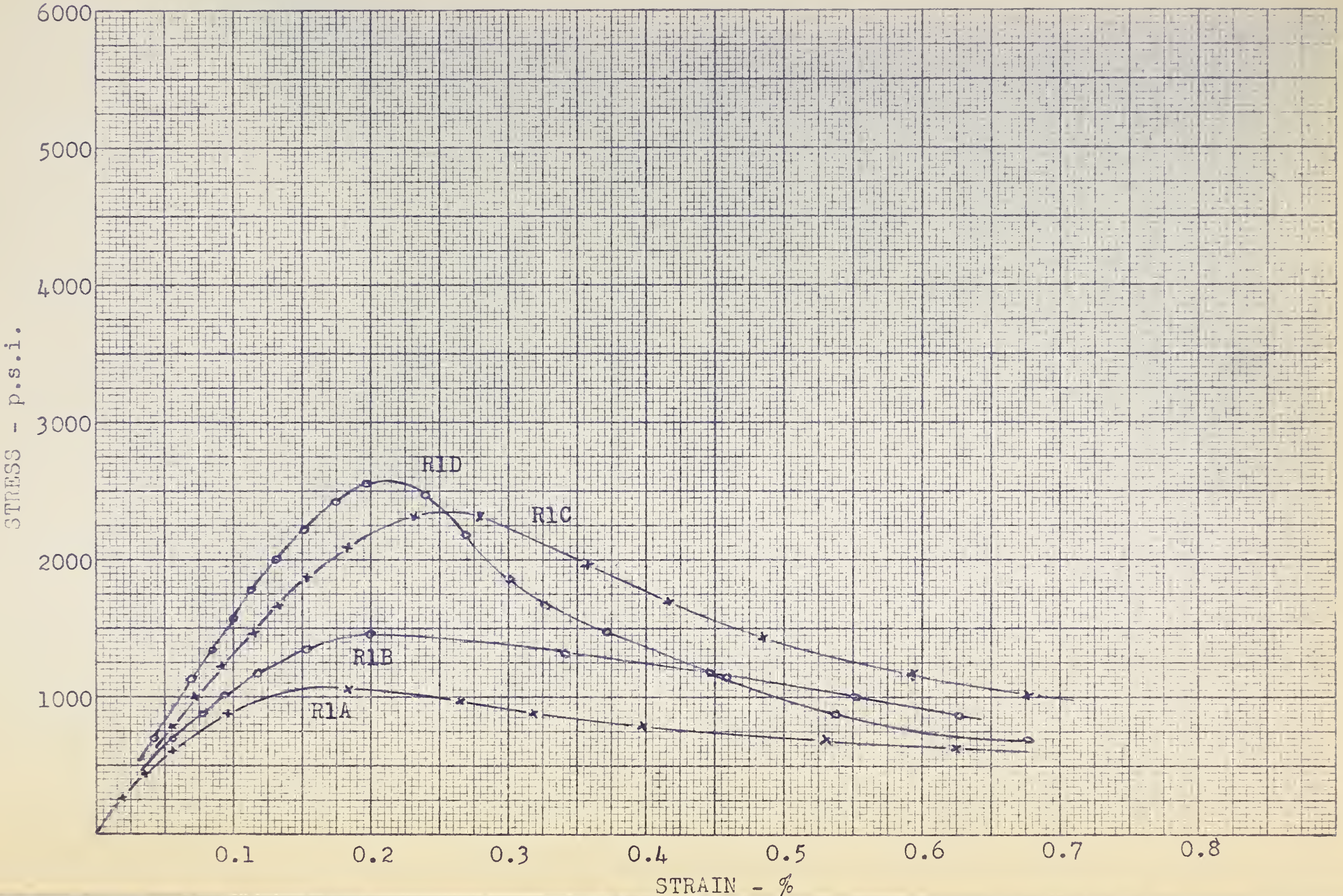


FIGURE 11

3000 p.s.i. - WITH RESTRAINT

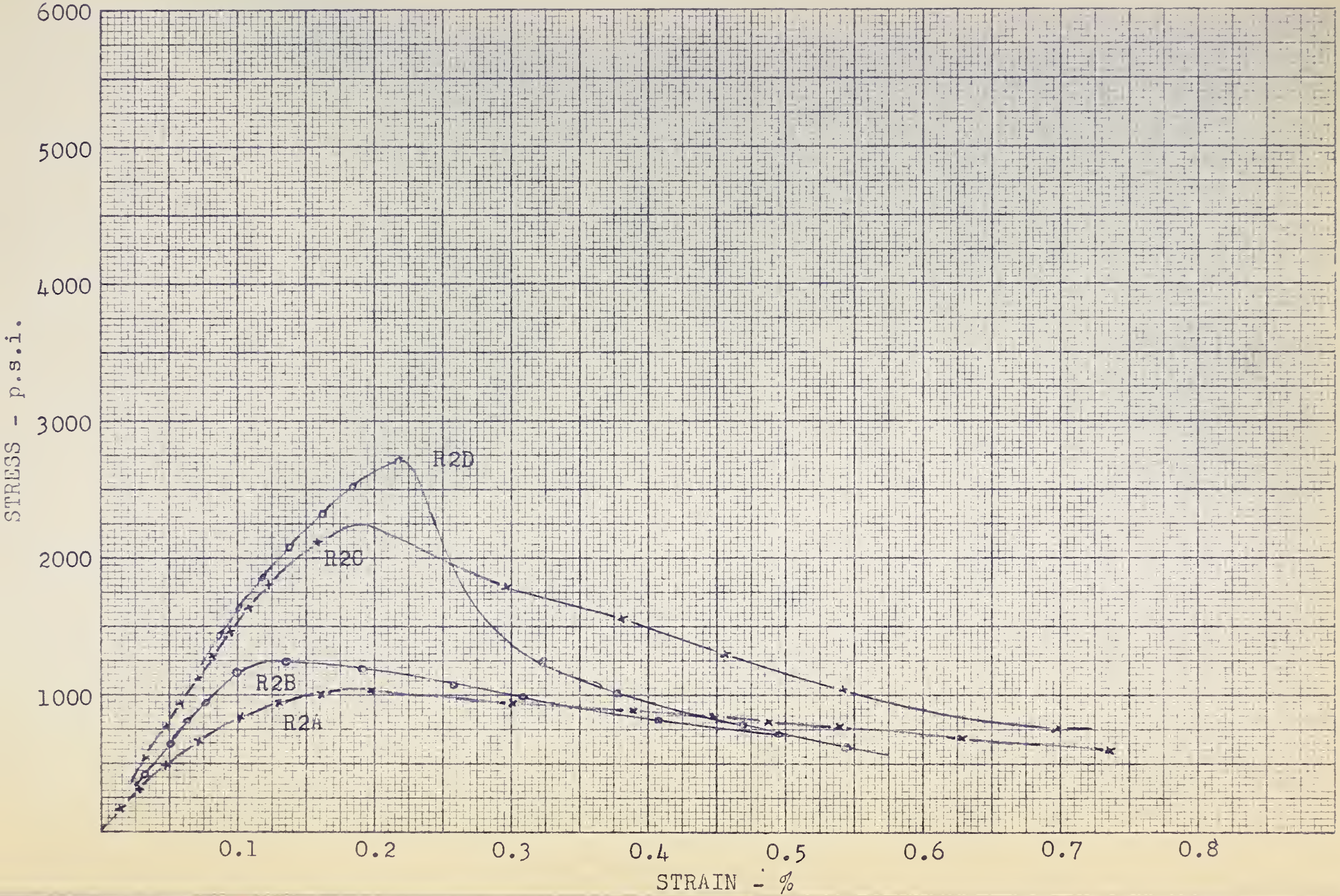


FIGURE 12

3500 p.s.i. - WITH RESTRAINT

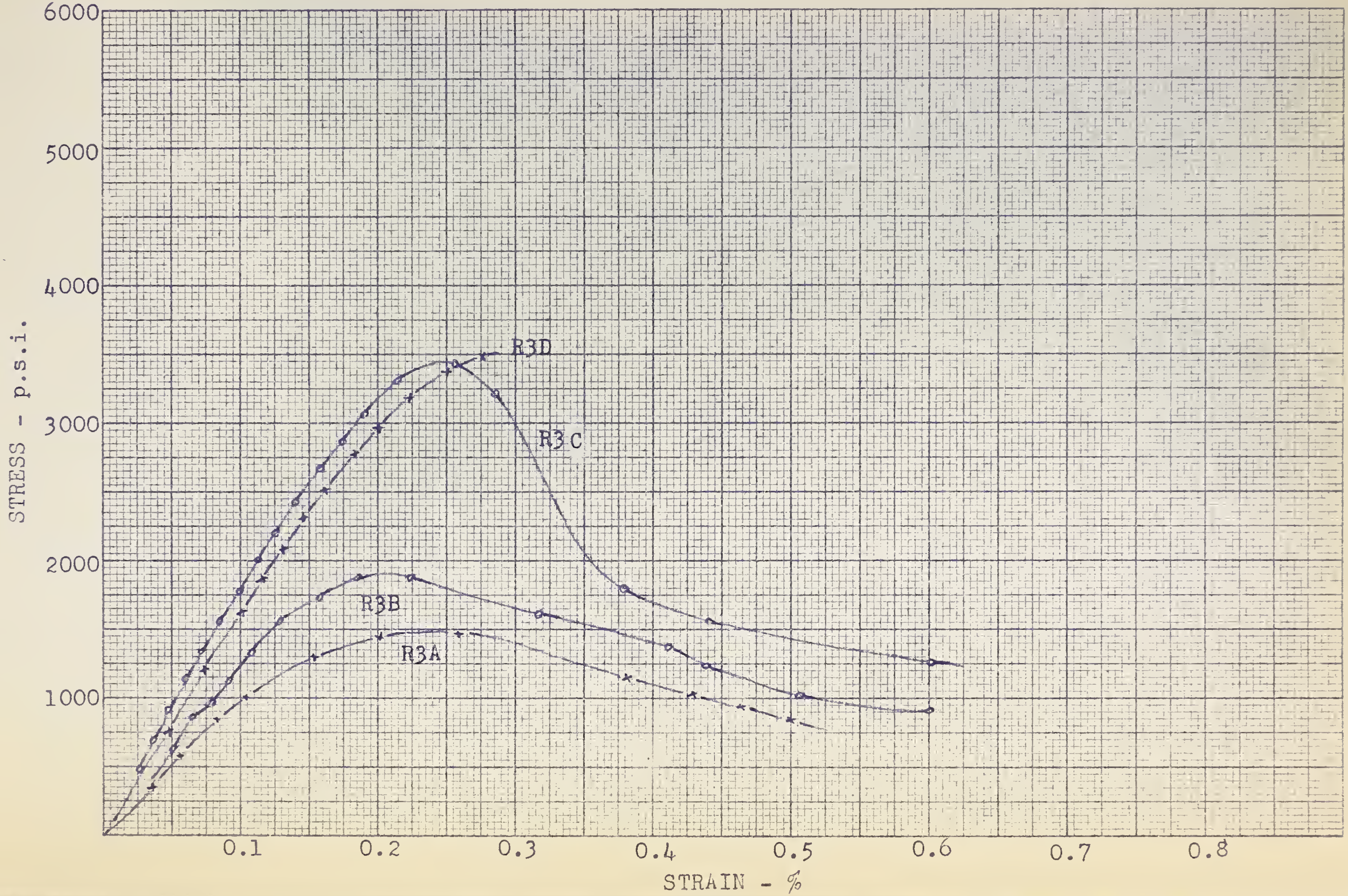


FIGURE 13

4000 p.s.i. - WITH RESTRAINT

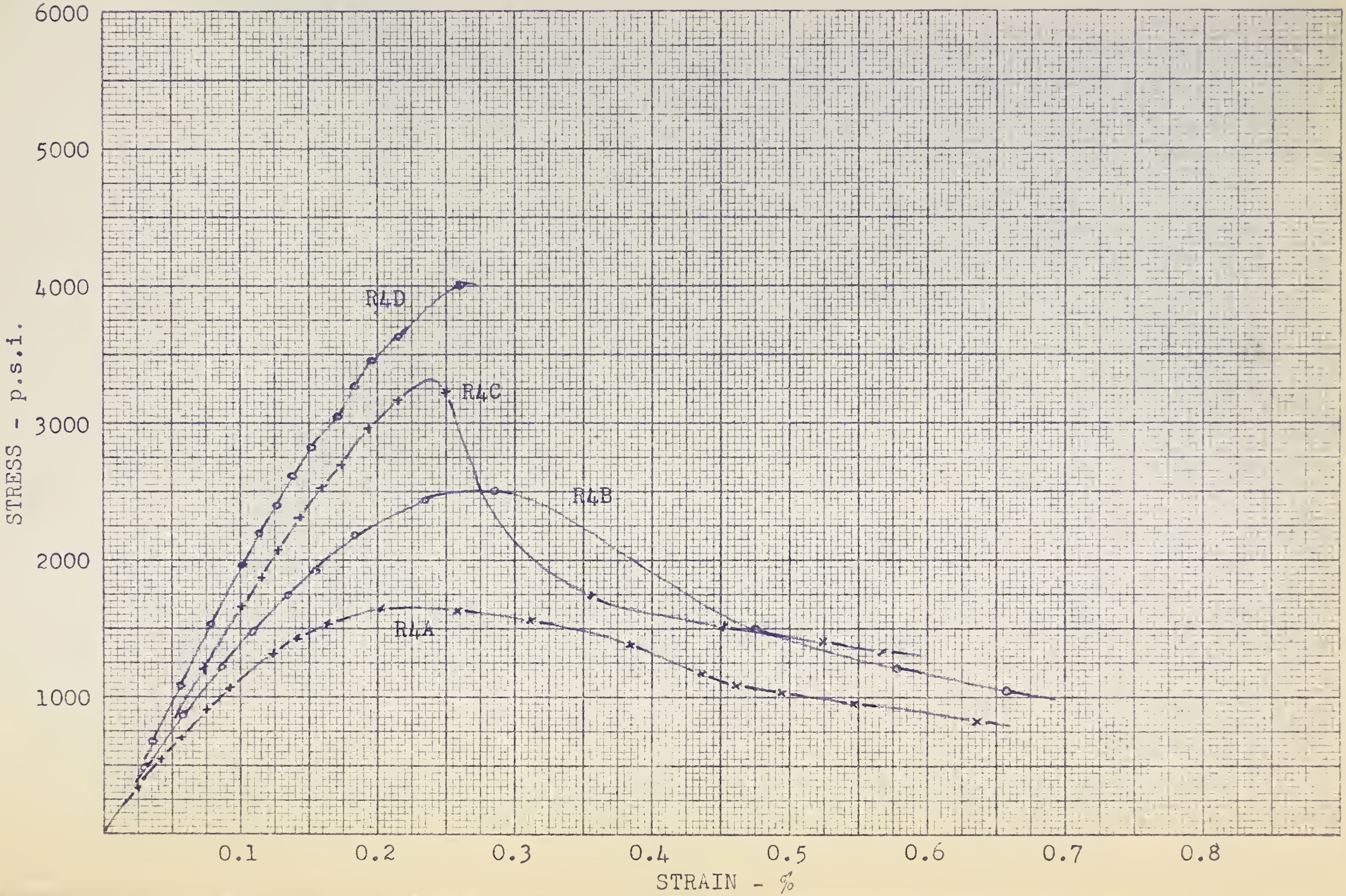


FIGURE 14

4500 p.s.i. - WITH RESTRAINT

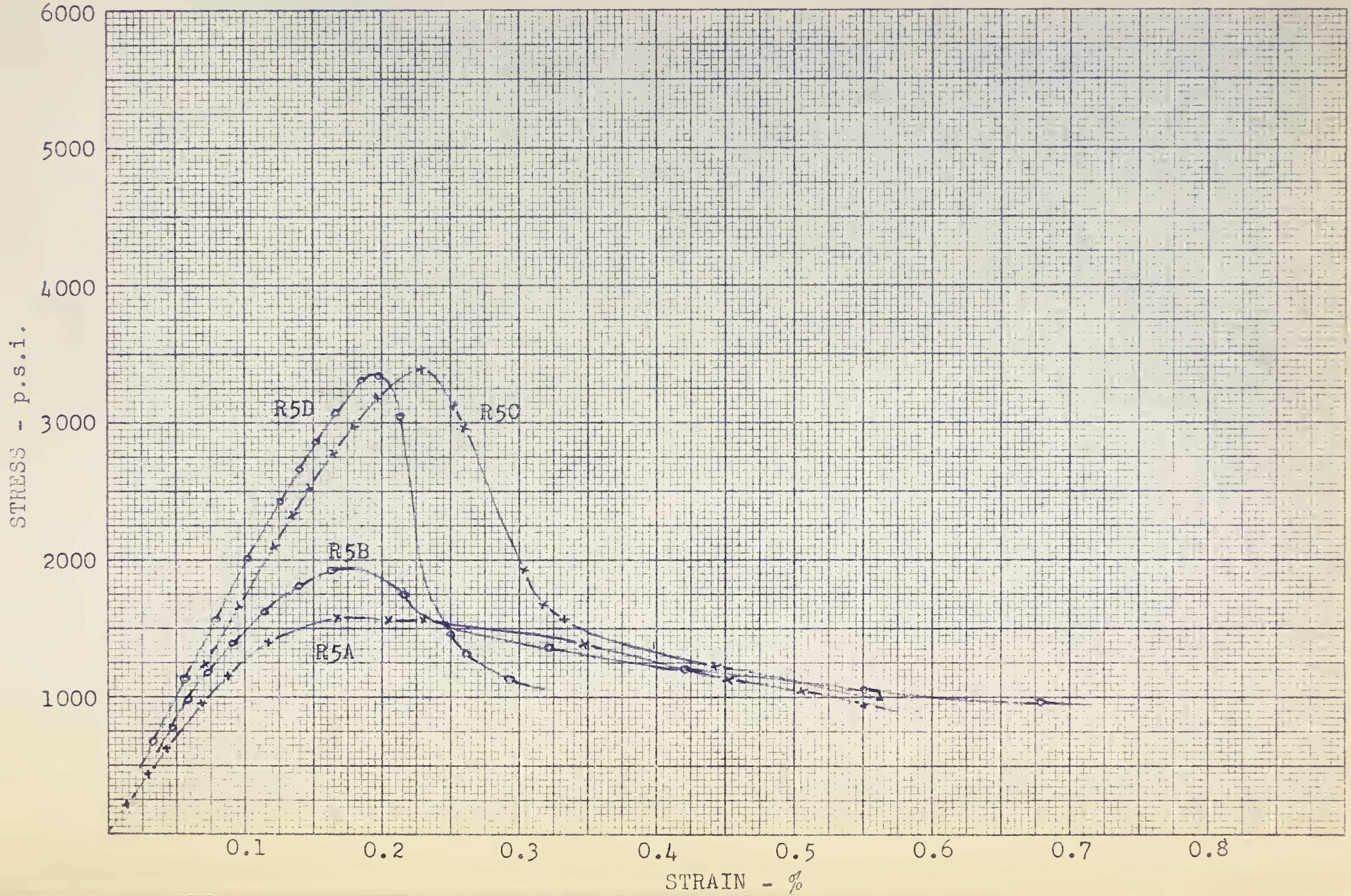


FIGURE 15

5000 p.s.i. - WITH RESTRAINT

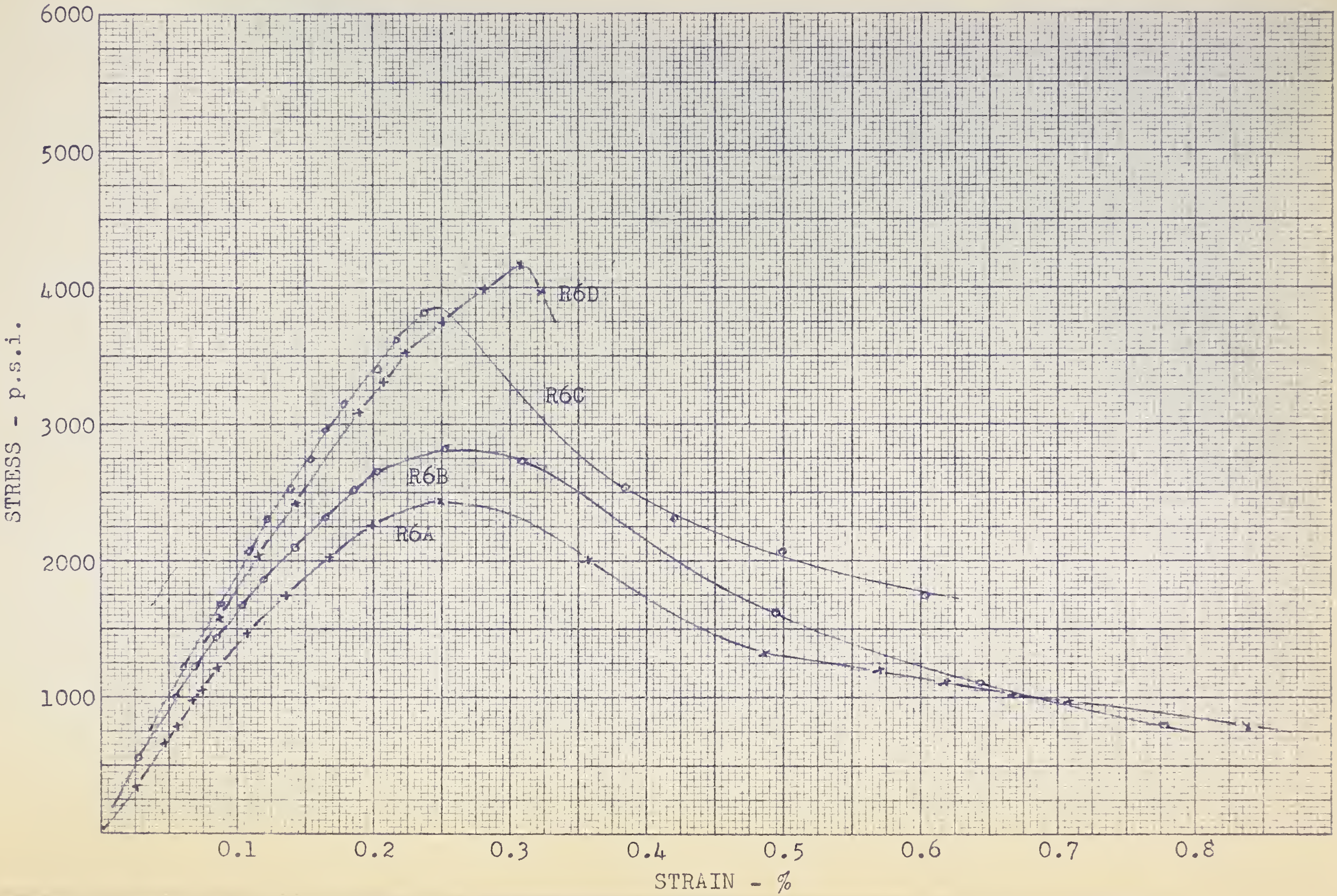


FIGURE 16

2500 p.s.i. - WITHOUT RESTRAINT
(AIR-CURED)

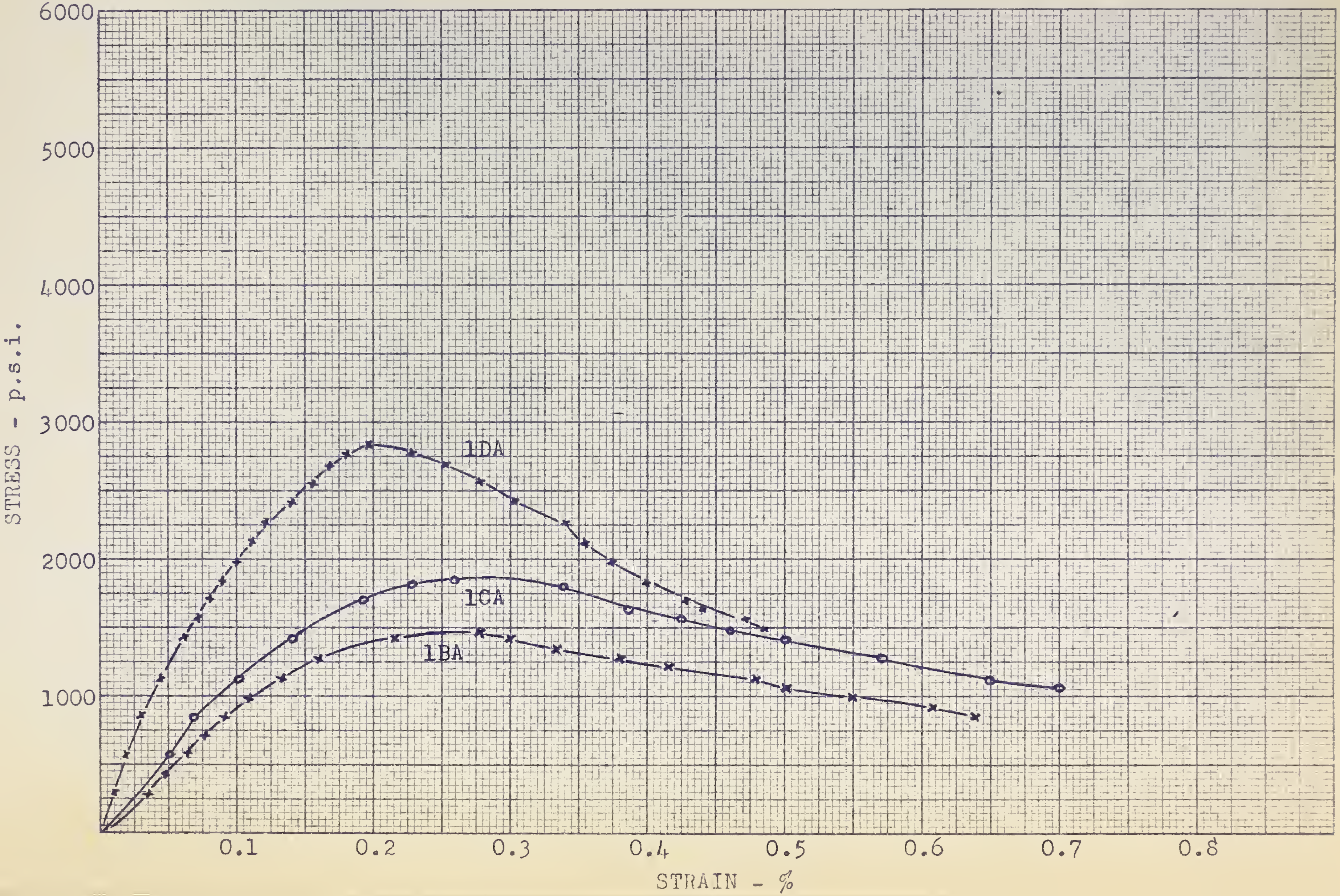
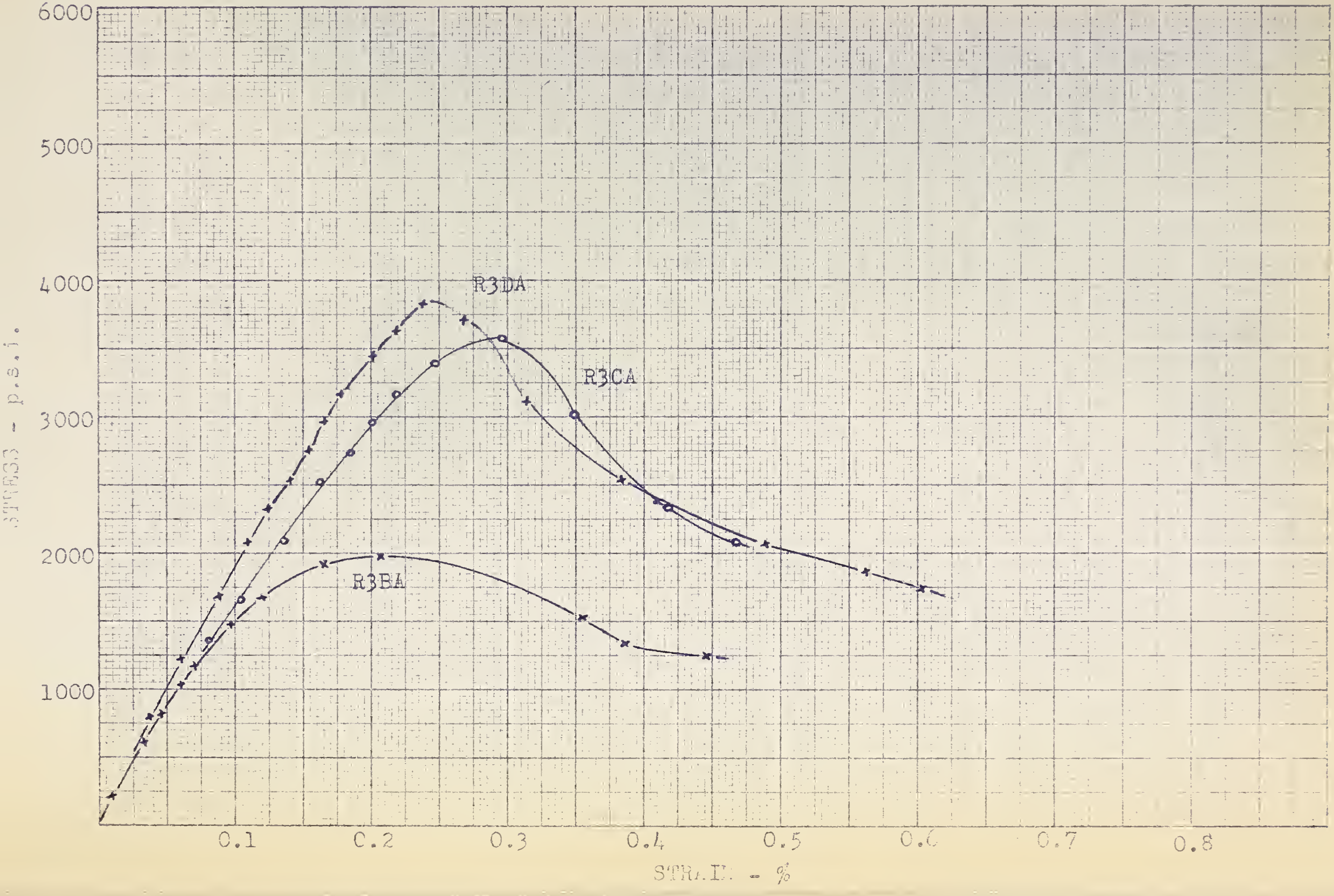


FIGURE 17

3500 p.s.i. - WITH RESTRAINT

(AIR-CURED)



A limiting strain based on 85% of the compressive strength beyond the ultimate load is the value used by several plastic and ultimate design theories in determining the size of the theoretical stress block, thus it was chosen as the limiting strain for this report. For all cylinders tested in this group (see figure 27) the limiting strain was found to be relatively a constant in the neighbourhood of 0.0033 in./in. Again, in determining this value, less consideration was given to cylinders having a compressive strength below 2000 psi.

The point at which the tests were stopped was dependent upon the rate of disintegration of the specimen, the calibrated range of the gauges, etc. and, therefore, no particular physical significance can be attributed to the termination point.

Similar tests were made on the cylinders in group (2) with the exception that the restraining springs were used. The results were in close agreement with those in group (1) and thus the remarks made there also apply in general to group (2). From figure 24, the modulus of elasticity for cylinders loaded with restraint can be expressed as follows:

$$E_c = 920{,}000 + 248\ f'c$$

This expression gives slightly larger values than the expression obtained for cylinders loaded without restraint. However, the limiting strain is decreased (figure 28) to 0.0029 in/in.

Although some improvement to curves of cylinders with higher strengths may have occurred by using the restraining springs, it is felt the results in this section are not as reliable as for group (1). Considerable difficulty was experienced in compressing the springs by a load (say 10,000 to 15,000 lbs.) prior to loading the specimen which was necessary to seat the springs properly. It was also felt that the springs were too flexible, i.e. spring constant too low for higher strength concretes, and they did not have sufficient deflection for light-weight concrete.

Because of the close agreement between groups (1) and (2) it was deemed satisfactory to test cylinders in group (3) without restraint. 48 cylinders were cured under various conditions and the results were plotted in figures 18 - 21.

Although the same design proportions were used for the mixes, the strengths obtained were lower in general than corresponding strengths for groups (1) and (2). This was surprising as early in the tests two cylinders were used to check the effect of this curing temperature on the compressive strength. Both cylinders were left in the forms for 24 hours, one was steam-cured for 24 hours and then placed in the moist room, while the other was placed directly in the moist room. Both were loaded at 36 hours. The cylinder which was steam-cured

FIGURE 18

2500 p.s.i. - WITHOUT RESTRAINT
(STEAM-CURED)

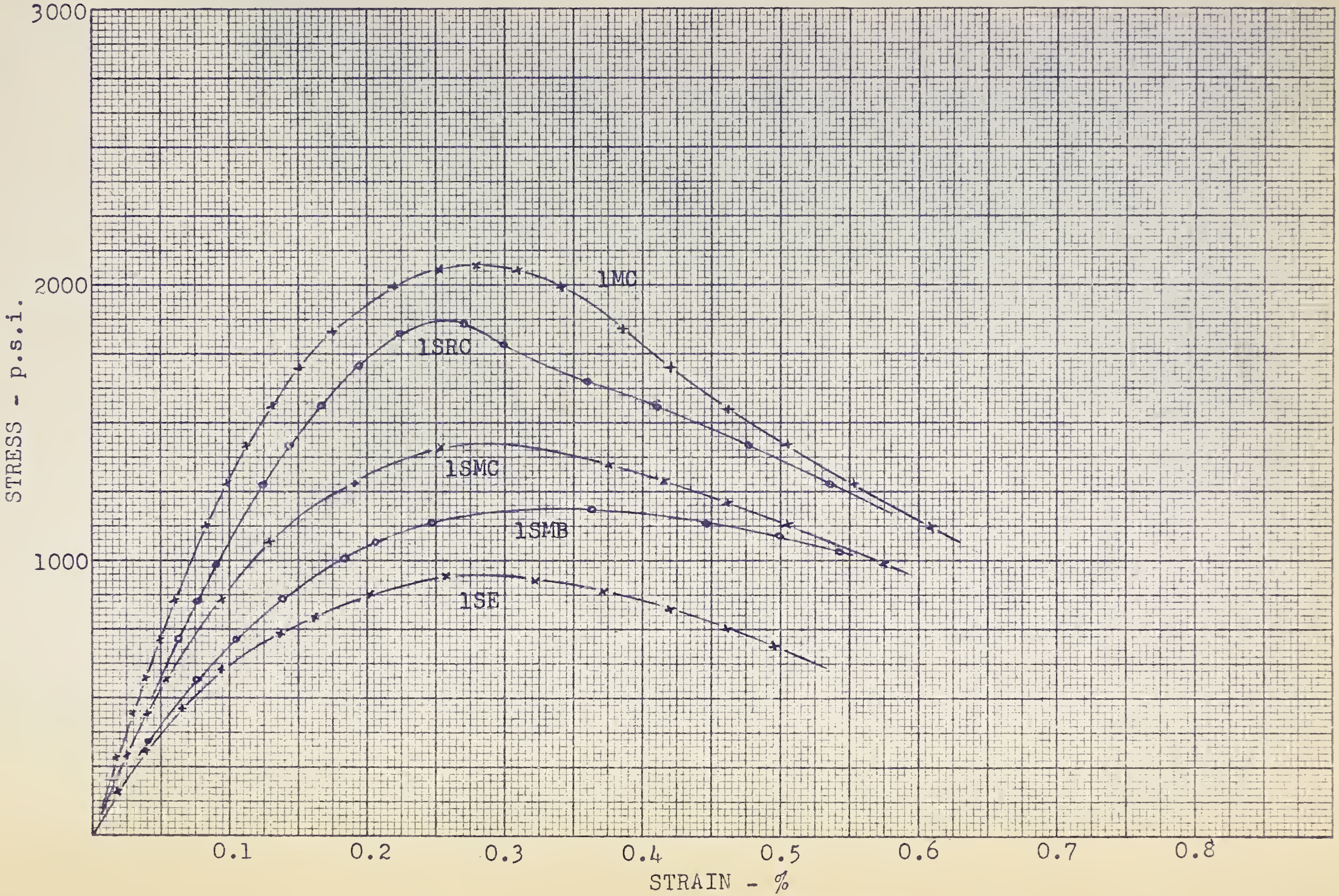


FIGURE 19

3000 p.s.i. - WITHOUT RESTRAINT

(STEAM-CURED)

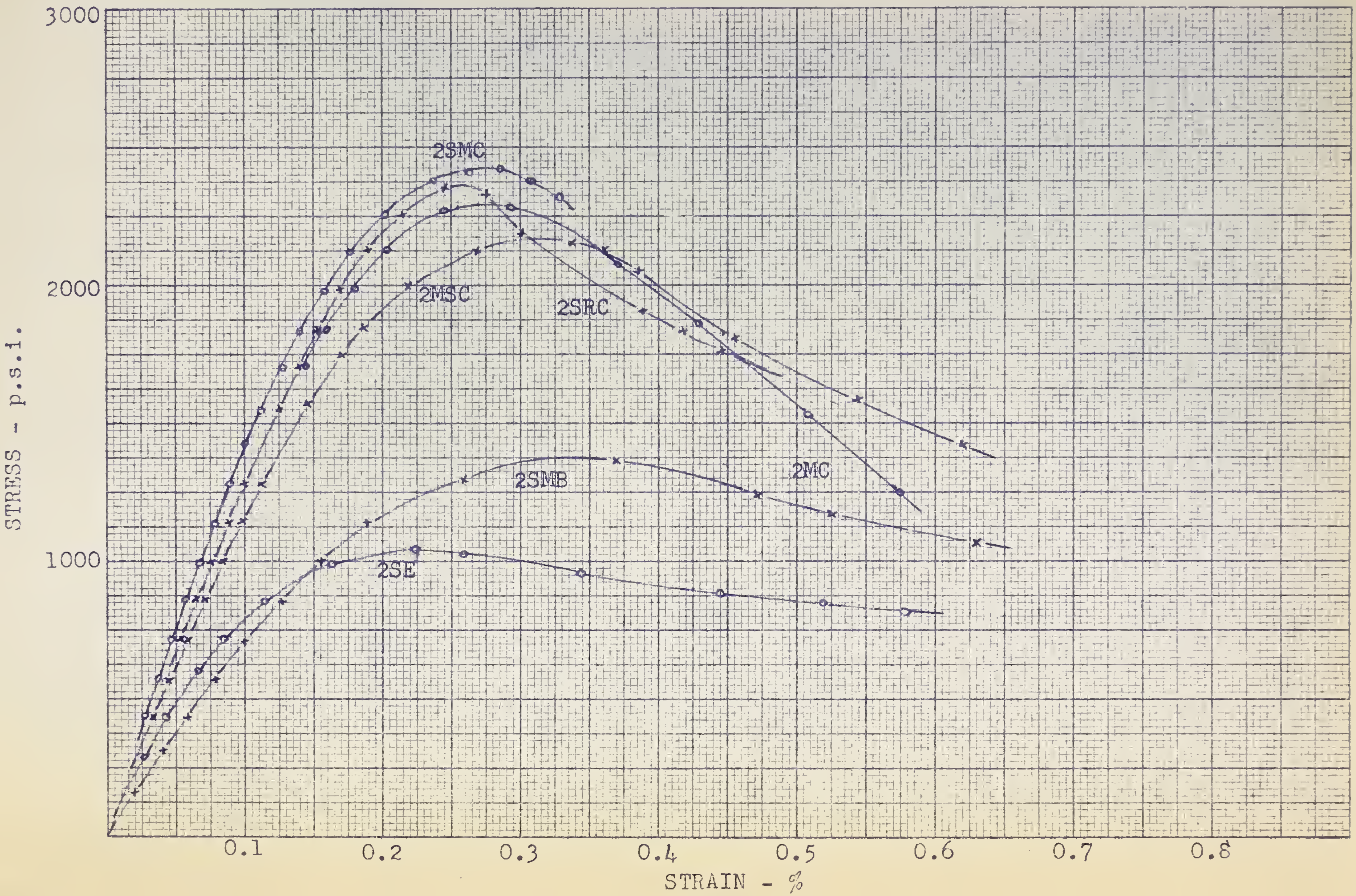


FIGURE 20

4000 p.s.i. - WITHOUT RESTRAINT

(STEAM-CURED)

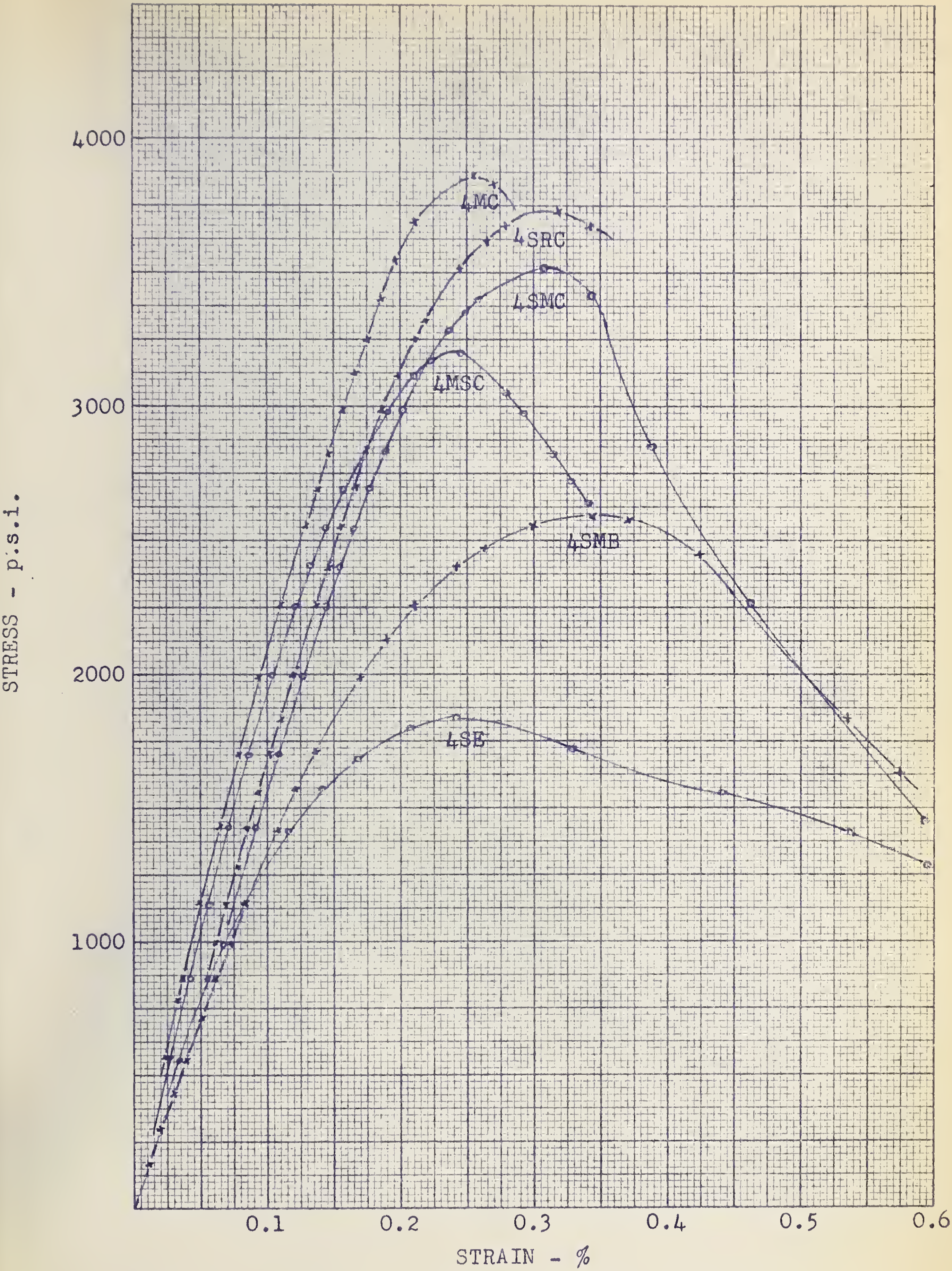


FIGURE 21

5000 p.s.i. - WITHOUT RESTRAINT

(STEAM-CURED)

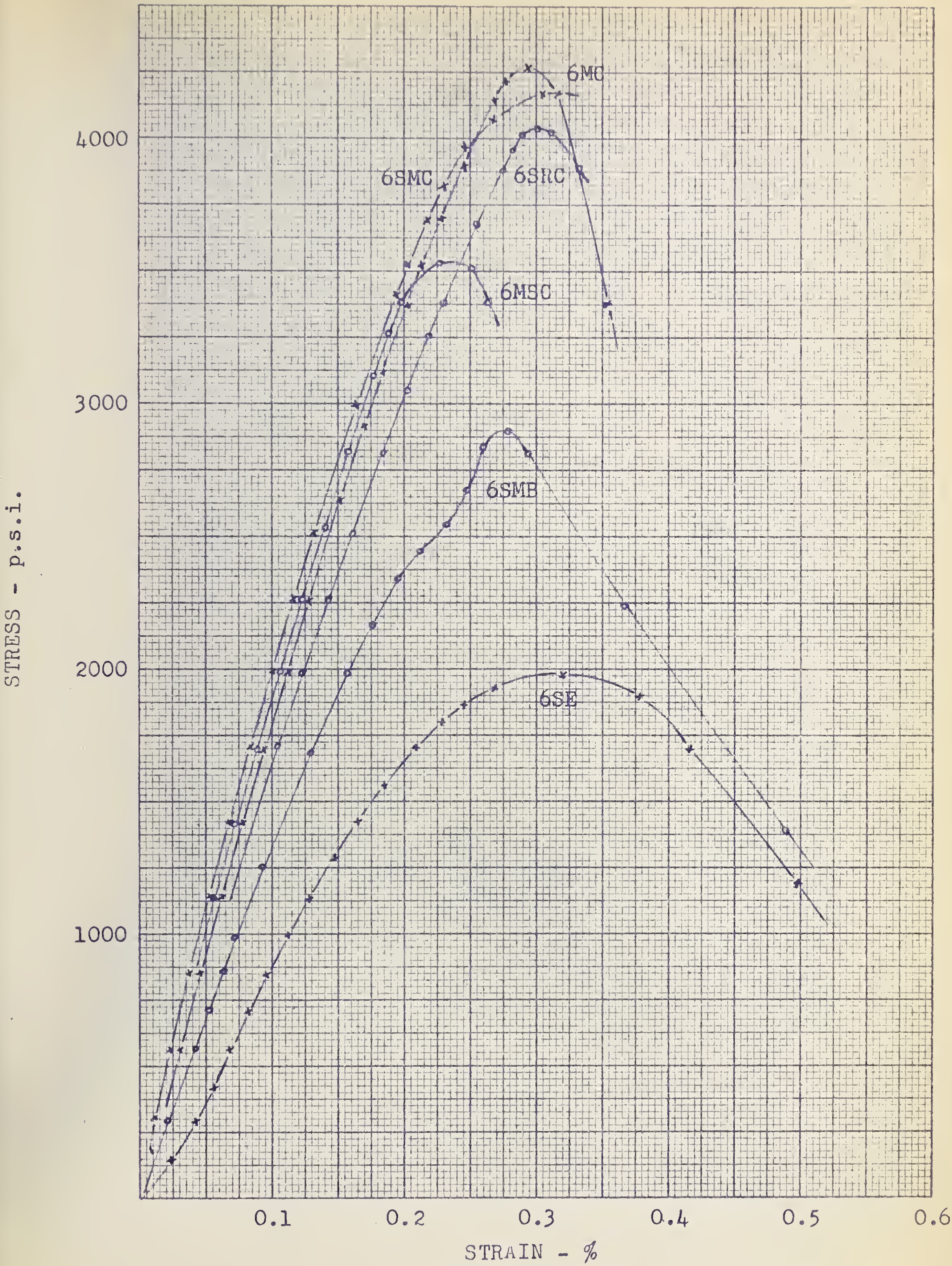
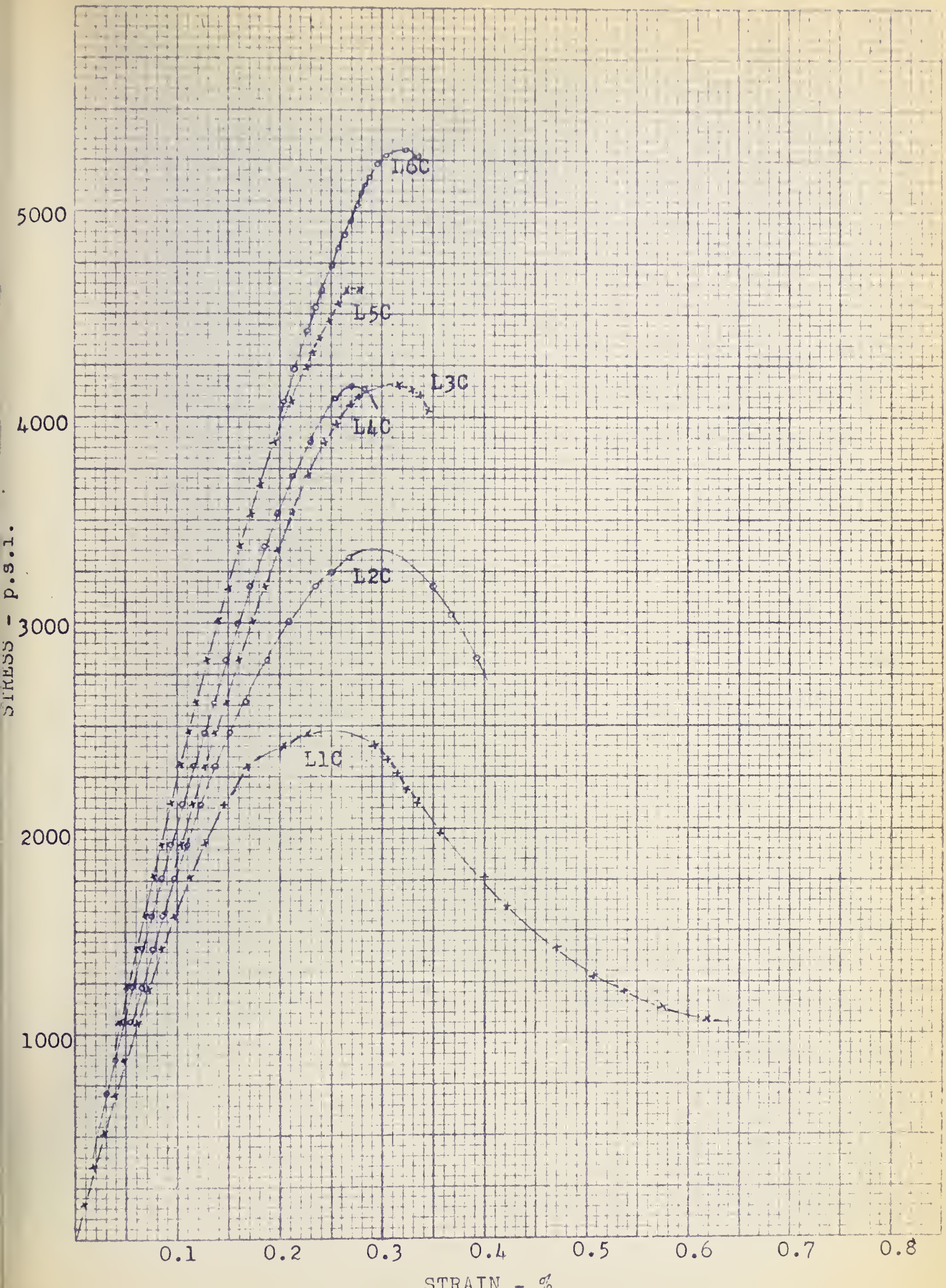


FIGURE 22

6" x 12" CYLINDER - WITHOUT RESTRAINT



carried a total load of 8200 pounds, while the moist cured cylinder carried only 3100 pounds, or less than half as much. However, since the control specimens (i.e. not steam-cured) were also lower than expected; it is felt that the fault lies with the mix rather than the curing temperature.

In general, after 28 days the standard moist cured specimens exhibited the highest strengths but were not significantly different from the specimens stream-cured for 24 hours and then moist cured or left in air until tested.

Delaying the steam-curing for 48 hours lowered the 28 day compressive strength from 5% to 10% on the basis of the results of this investigation. However, more extensive tests would be required to determine whether this loss of strength is permanent, or whether at longer intervals, say 42 days, the strength would have increased to be comparable to the other strengths.

The type of cure seems to have little effect on the modulus of elasticity and the limiting strain. There seems to be no fixed pattern that distinguishes these constants as peculiar to one type of cure. The modulus of elasticity for group (3) tests (see figure 25) can be expressed as follows:

$$E_c = 900,000 + 220 f'c$$

The limiting strain was determined as 0.0035 in./in. (See figure 29).

Since all three groups yielded results that agreed closely, it was considered valid to combine the results into one plot. The modulus of elasticity (see figure 26) resulting from this can be expressed as follows, again neglecting cylinders with compressive strengths below 2000 psi.

$$E_c = 900{,}000 + 230\ f'c$$

From figure 30 the limiting strain is determined as 0.00325 in./in.

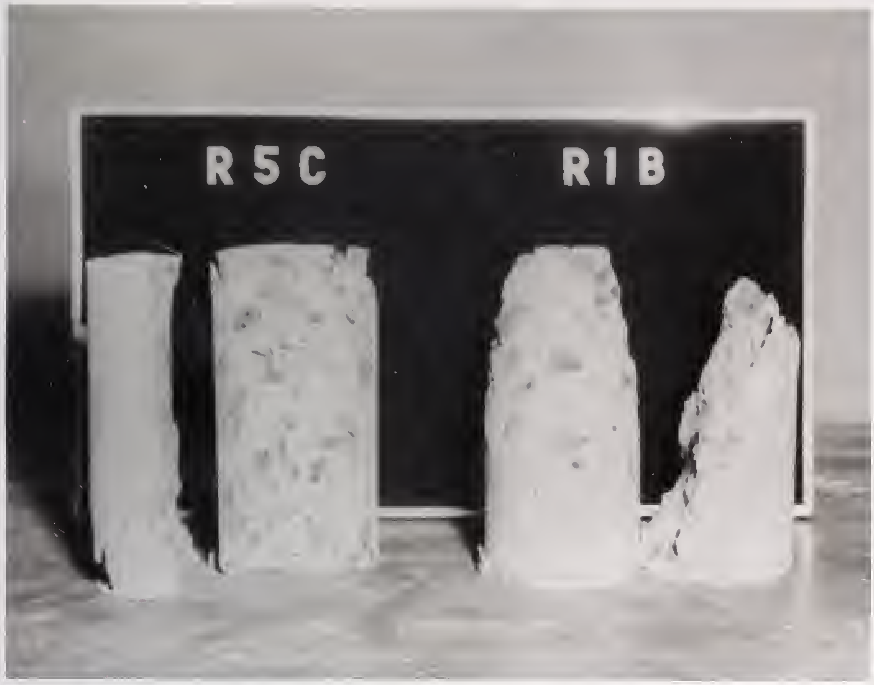
If the points in figure 26 are enclosed by two curves, along the upper and lower boundaries of the scattered points, it is seen that a curve drawn mid-way between these boundary curves, will give the value for the modulus of elasticity for any given value of the compressive strength. It is also noted that this curve passes through the origin which is to be expected.

Any curve passing through 3 known points not in a straight line can be approximated by a second degree parabola. Choosing points corresponding to compressive strengths of 0, 2500 and 5000 psi., the following expression was derived: $f'c = 1.19 \times 10^{-9} (E_c)^2 - 1.19 \times 10^{-4} E_c$

$$= 1.19 \times 10^{-4} E_c (10^{-5} E_c - 1)$$

This expression yields results for intermediate values that are in close agreement with the experimental curve and thus is given as the best relationship between these values.

It was observed that cylinders under 3000 psi. compressive strength failed with the typical shear fracture, with the shear plane approximately 30° to the longitudinal axis. However, cylinders above this value failed by cracking vertically. Photograph 9 shows this phenomenon clearly, the cylinder on the right was cast from a 2500 psi. mix, while the one on the left was poured from a 4500 psi. mix. Although these particular cylinders were loaded with the use of the restraining springs, the same type of failures were noted for those tested without restraint. Similarly, (see photograph 10) the same trend is illustrated for cylinders that were steam-cured. While these cylinders failed definitely in one pattern or the other, many cylinders in the vicinity of 3000 psi. failed as a combination, i.e. shear failure near the ends and vertical cracking at the centre.



Photograph 9 - Typical Failures
Tested with Restraint

Photograph 10 - Typical Failures
Steam-cured

TABLE 6

E_c and e_L For Cylinders

Loaded Without Restraint

Design Strength	2500			3000			3500			4000			4500			5000		
Age	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L
3 days	650	78	.46	1325	132	.49	1620	129	.32	1350	135	.39	2350	131	.34	2000	134	.37
3	770	92	.41	1500	95	.42	1650	141	.30	--	--	--	2425	132	.37	2075	127	.38
7	1175	94	.44	2150	147	.34	2300	157	.31	2100	157	.36	2900	161	--	3050	140	.37
7	1300	128	.41	2320	155	.34	2540	153	.33	2120	148	.42	2940	141	.36	3200	183	.30
7 (Air)	1475	94	.38	2675	125	.37	2690	179	.31	2270	116	.38	2625	165	.31	2850	132	.31
28	2020	147	.37	3060	142	.35	3120	193	.26	3800	157	.35	4150	160	--	4000	176	--
28	2260	163	.32	3550	150	--	3770	141	.33	3920	173	--	4250	180	--	3575	176	--
28	2400	150	.32	3500	195	--	3950	215	--	4000	204	--	4650	164	--	4200	234	--
28 (Air)	1850	111	.38	3650	183	--	3900	156	.36	3700	185	.28	--	--	--	3400	204	--
42	2450	135	.29	3400	169	.34	4350	168	.33	4550	182	--	4525	184	--	4400	208	--
42	2450	184	.28	3700	180	--	--	--	--	4550	165	--	4650	187	--	4925	191	--
42 (Air)	2850	228	.30	3500	161	.33	4150	167	--	--	--	--	4800	163	--	5100	254	--
28 (Large)	2250	185	--	3100	174	--	3650	200	--	3950	220	--	4000	216	--	5175	171	--
28 (Large)	2450	178	.31	3375	190	.35	4150	185	--	4625	233	--	4175	209	--	5300	212	--

Note:- f'c (breaking strength) psi.; E_c (modulus of elasticity) X 10^4 psi.; e_L (limiting strain)%.

TABLE 7

E_c & e_L for Cylinders

Loaded With Restraint

Design Strength	2500			3000			3500			4000			4500			5000		
Age	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L
3	1050	109	.31	1025	103	.35	1760	210	.28	1550	121	.31	1600	132	.34	2430	135	.31
3	1050	109	.31	--	--	--	1870	157	.32	1675	113	.35	2050	189	.28	--	--	--
7	1020	190	.21	1100	132	.32	1500	113	.39	2475	133	.35	1925	159	.24	2850	162	.34
7	1450	128	.38	1250	125	.27	1900	152	.31	2700	216	.26	--	--	--	2550	148	.19
7 (Air)	1350	127	.25	1250	125	.19	1970	160	.30	--	--	--	1840	95	.36	3700	185	.31
28	2350	139	.35	2100	140	.28	2700	164	.22	2860	141	.27	2600	226	.26	3150	210	--
28	2600	214	.27	2175	157	.25	--	--	--	3300	159	.27	3200	191	.21	3800	237	--
28	--	--	--	2250	157	.26	3410	171	.29	3350	172	--	3400	169	.26	3850	186	.29
28 (Air)	--	--	--	--	--	--	3550	250	.35	3525	141	.37	3200	153	.30	--	--	--
42	2700	161	.26	--	--	--	2820	187	.24	4010	185	--	--	--	--	--	--	--
42	--	--	--	2750	169	.24	3550	157	--	4400	147	--	3550	190	.22	4130	167	--
42 (Air)	2080	195	.19	2820	181	.20	2620	165	.23	5000	170	--	3500	225	.23	--	--	--

Note:- f'c (breaking strength) psi.; E_c (Modulus of Elasticity) X 10^4 psi.; e_L (limiting strain) %.

TABLE 8.

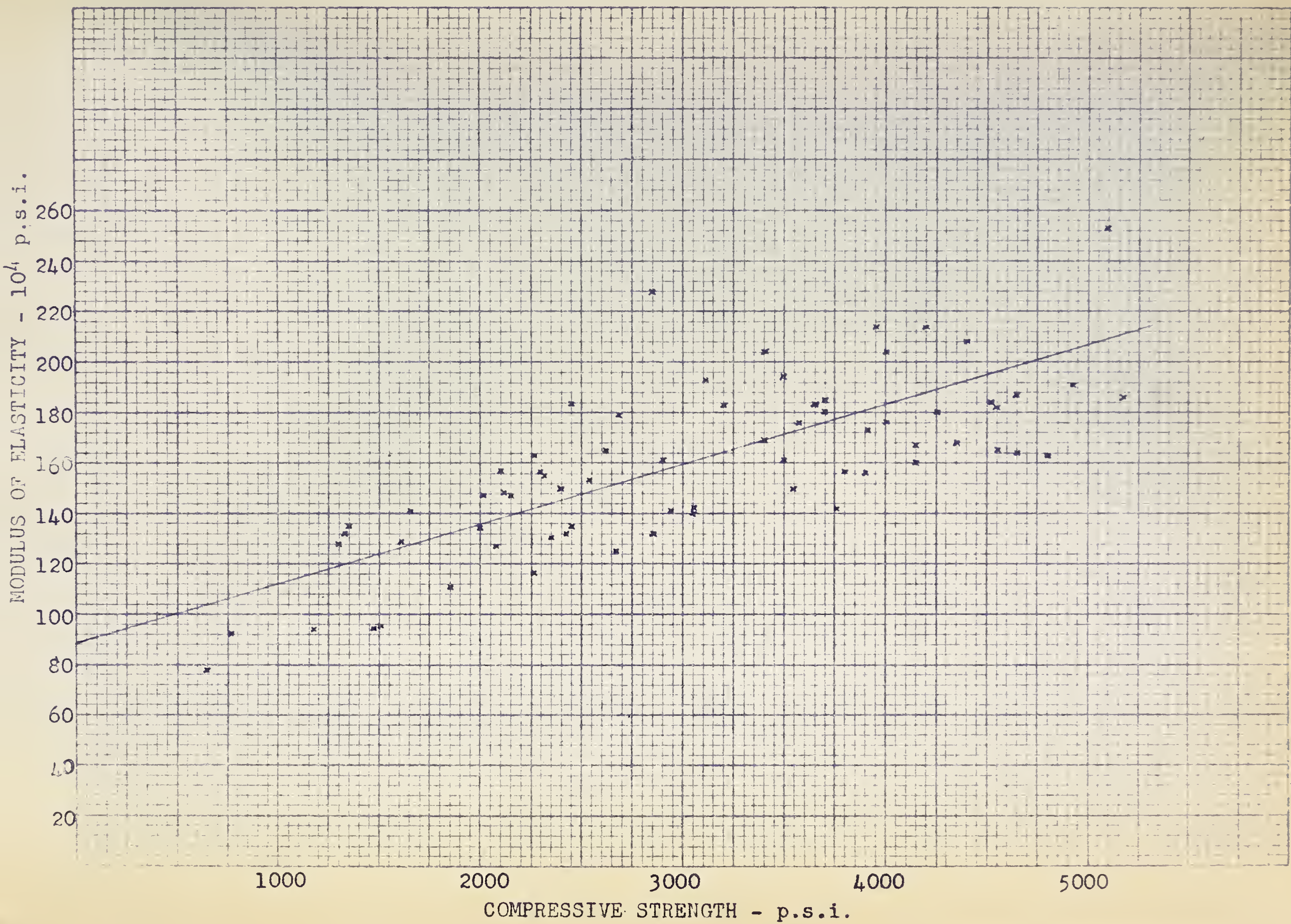
E_c and e_L for steam-cured

cylinders tested without restraint.

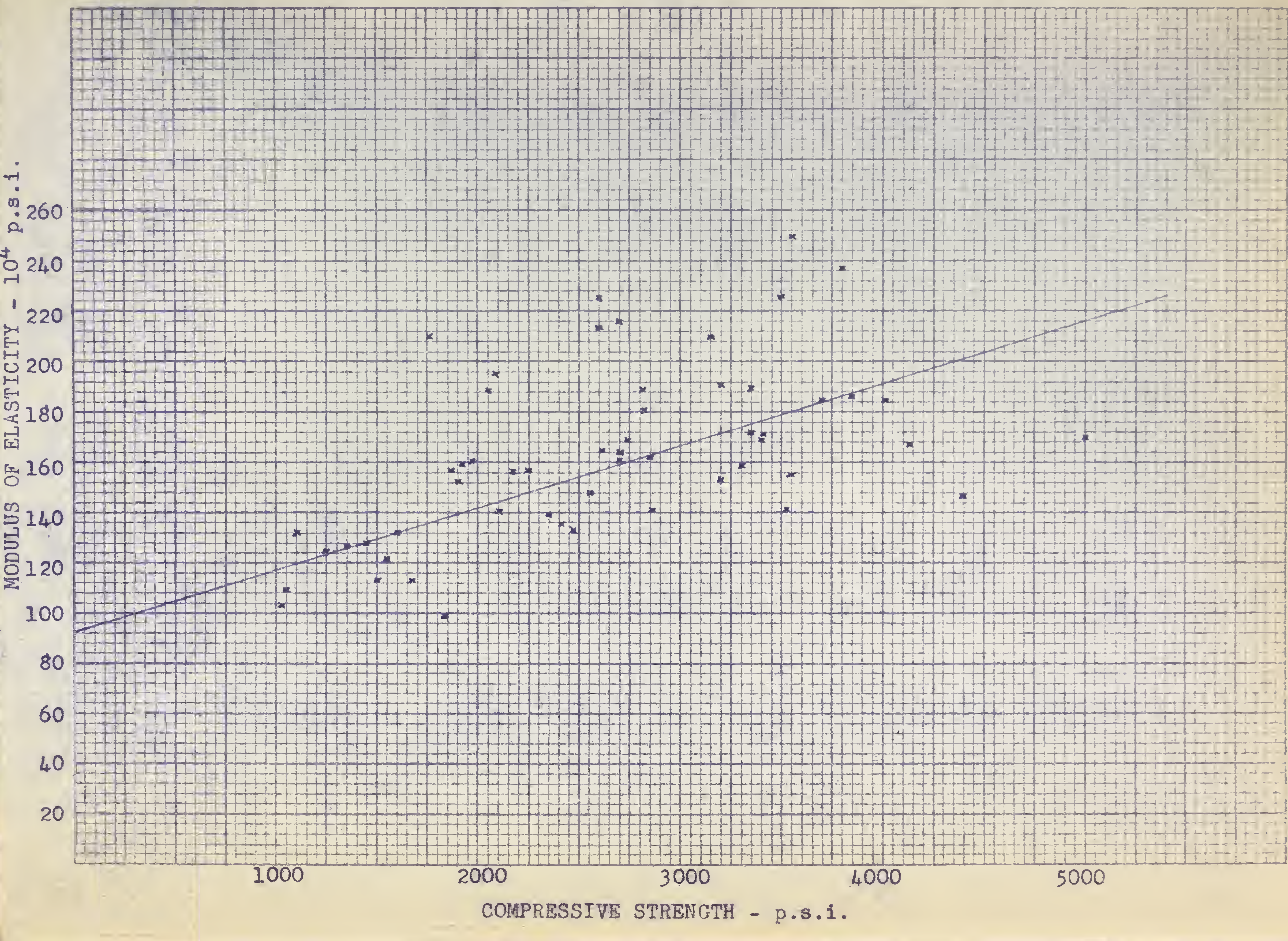
DESIGN STRENGTH	2500			3000			4000			5000		
AGE	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L	f'c	E_c	e_L
SE	930	73	.43	800	120	.33	1850	150	.43	1925	124	.37
SE	--	--	--	1030	111	.46	1960	157	.32	1975	190	.41
SMB	1120	54	.53	1200	115	--	2575	137	.47	2900	137	.34
SMB	1180	76	--	1350	75	.55	2675	130	.43	3050	180	.29
SRC	1875	117	.38	--	--	--	4000	118	--	4050	167	--
SRC	1420	105	.45	2370	128	.35	3730	164	--	3950	124	--
MSC	1900	171	.30	2150	120	.44	3125	150	.37	3775	170	--
MSC	1650	165	.36	--	--	--	3200	148	.33	3550	196	--
SMC	1700	139	.57	2025	114	.48	--	--	--	4175	198	--
SMC	2000	140	.35	2425	150	--	3550	153	.37	--	--	--
MC	2000	129	.41	2300	136	.40	--	--	--	3775	153	--
MC	2075	130	.40	--	--	--	3850	221	--	4275	179	.34

f'c (compressive strength) p.s.i.; E_c (Modelus of Elasticity) x 10^4 p.s.i.;
e_L (limiting strain) %

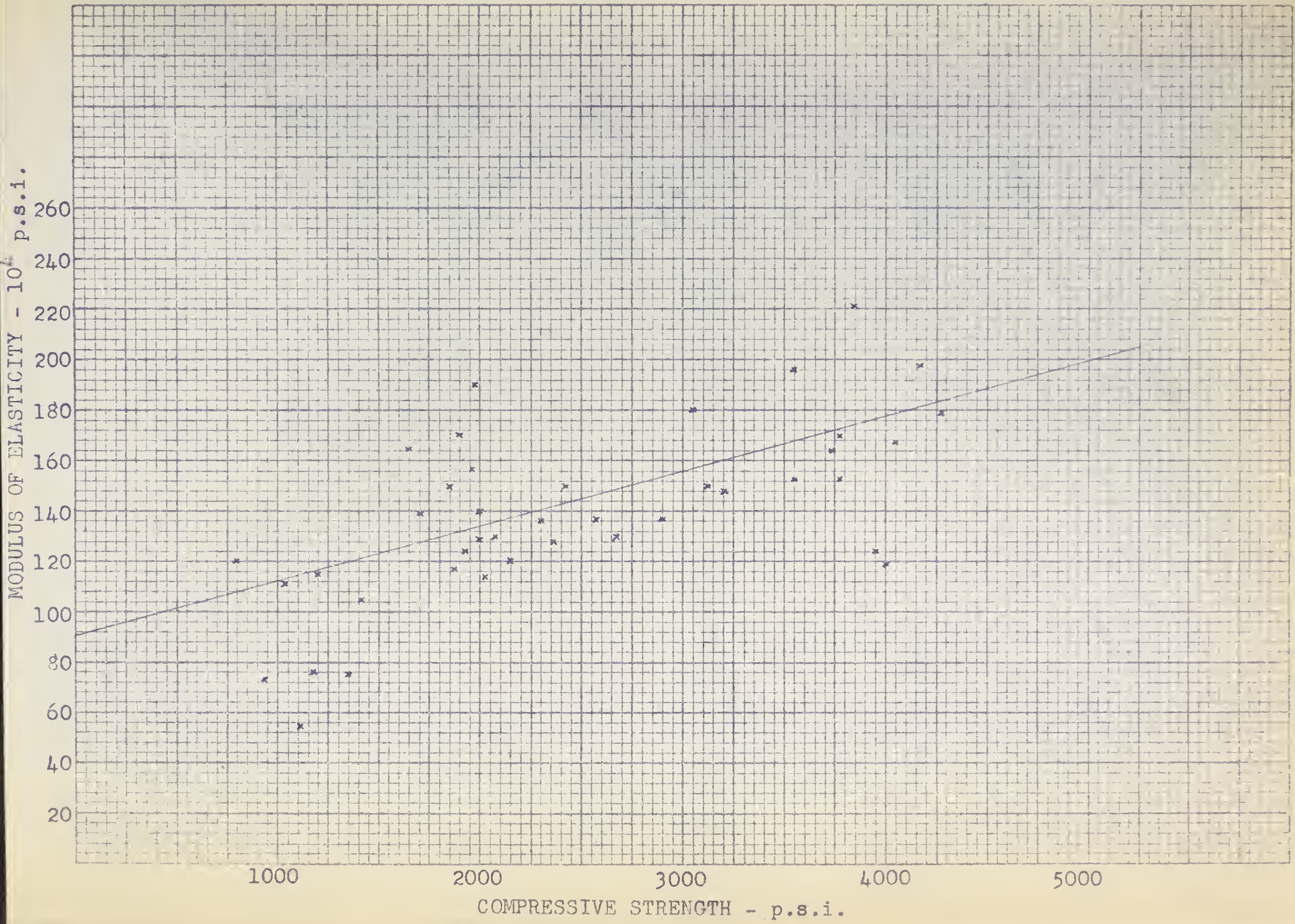
MODULUS OF ELASTICITY - WITHOUT RESTRAINT



MODULUS OF ELASTICITY - WITH RESTRAINT



MODULUS OF ELASTICITY - STEAM-CURED



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MODULUS OF ELASTICITY

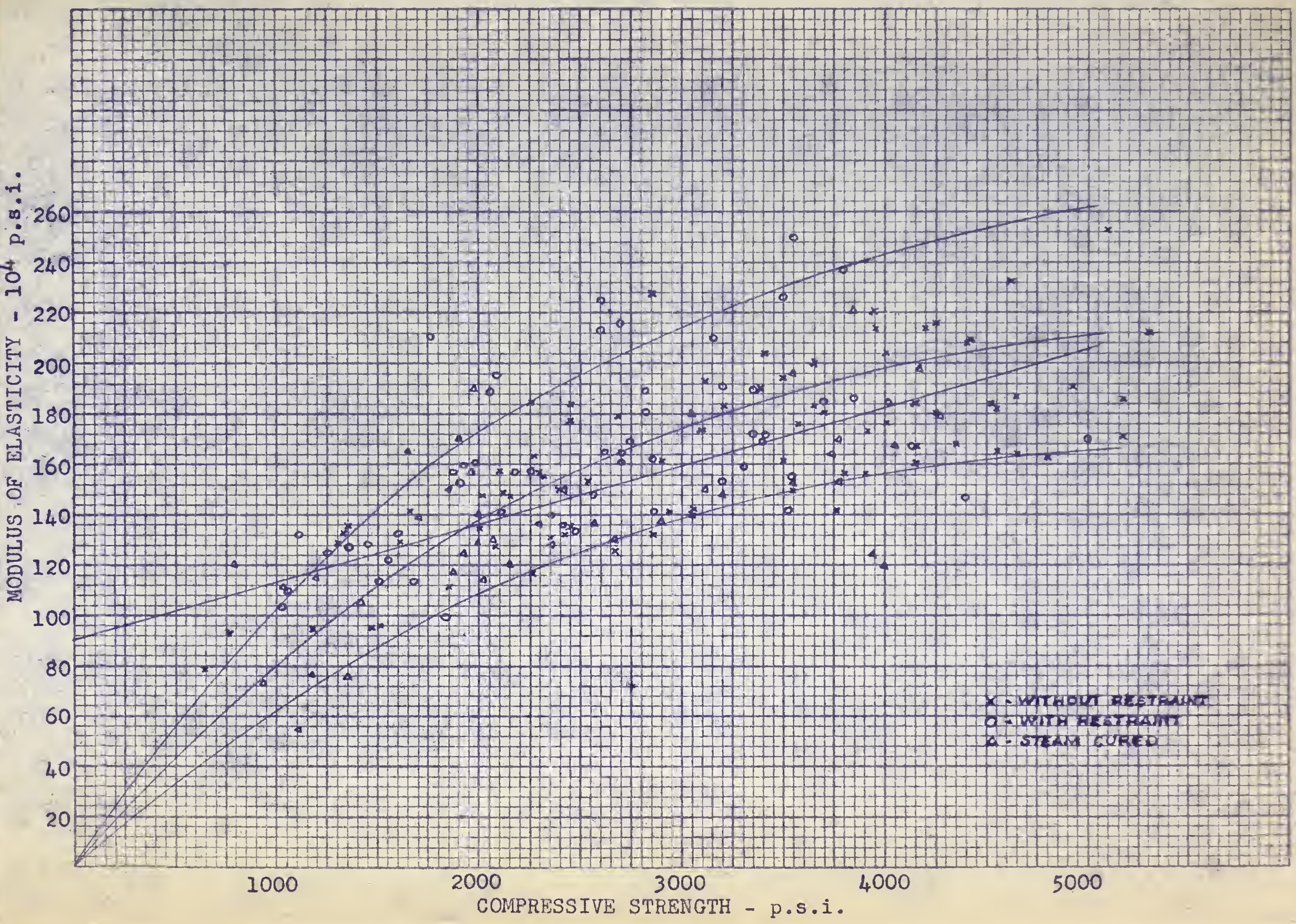


FIGURE 27

LIMITING STRAIN - WITHOUT RESTRAINT

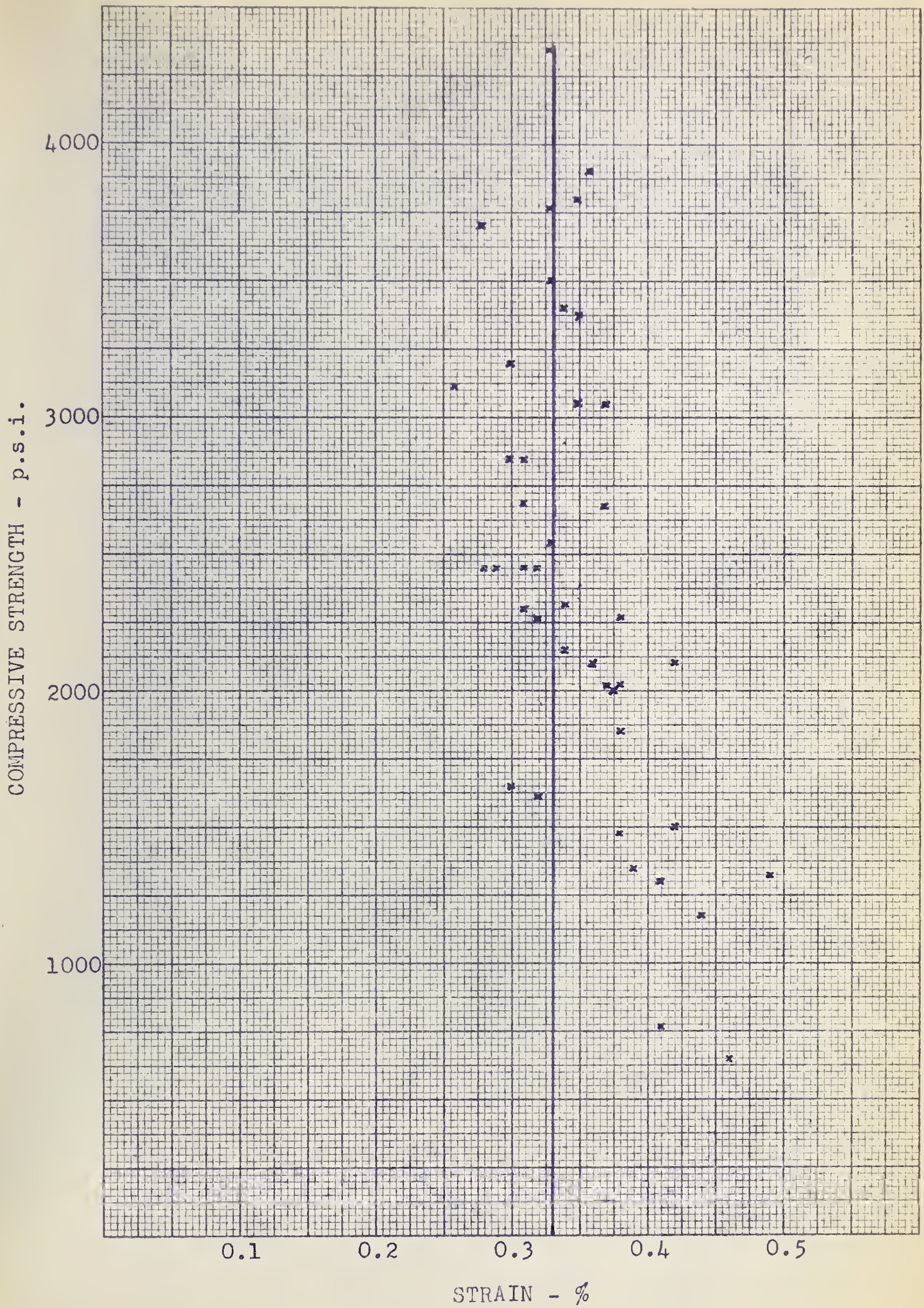


FIGURE 28

LIMITING STRAIN - WITH RESTRAINT

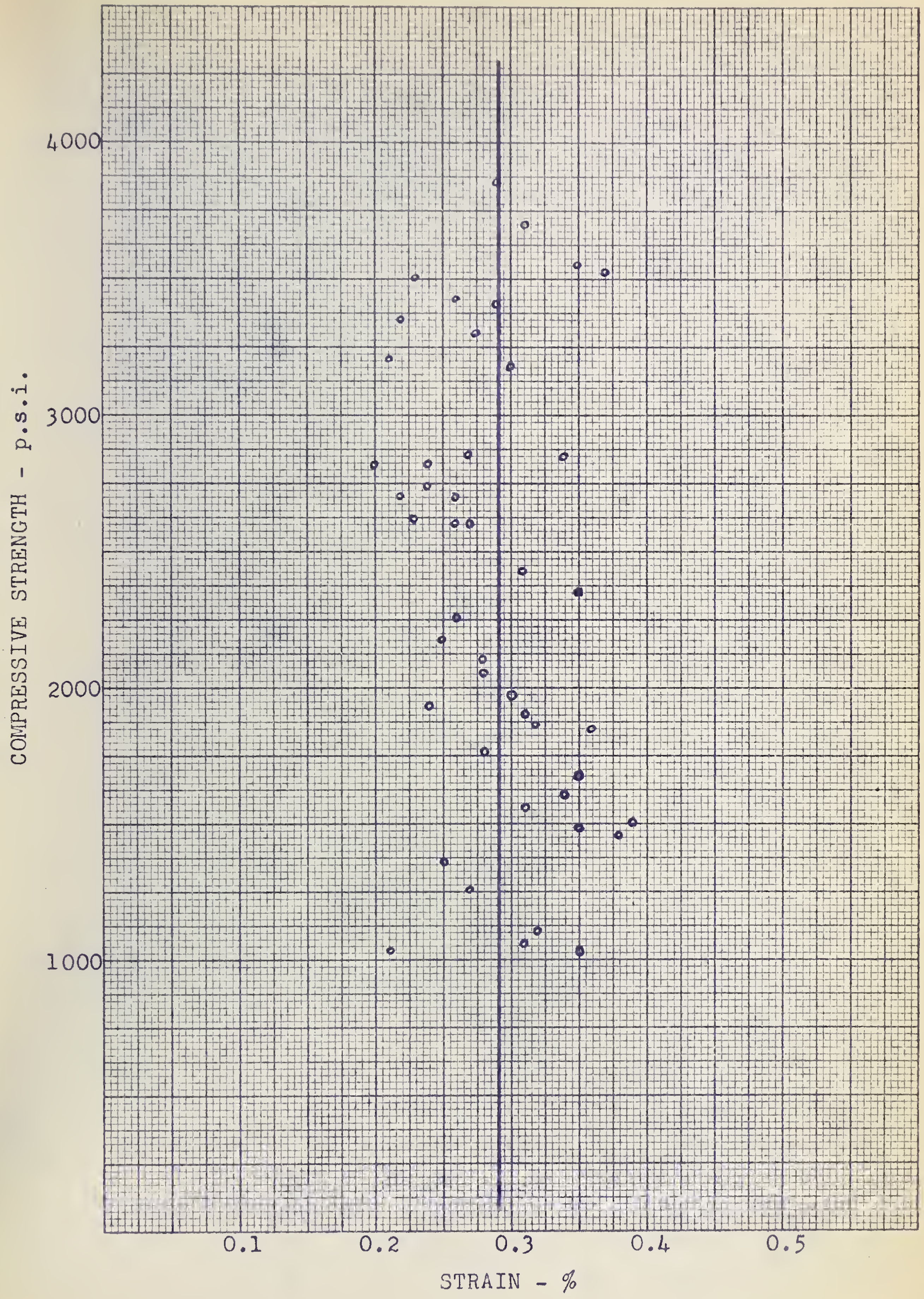


FIGURE 29

LIMITING STRAIN - STEAM-CURED

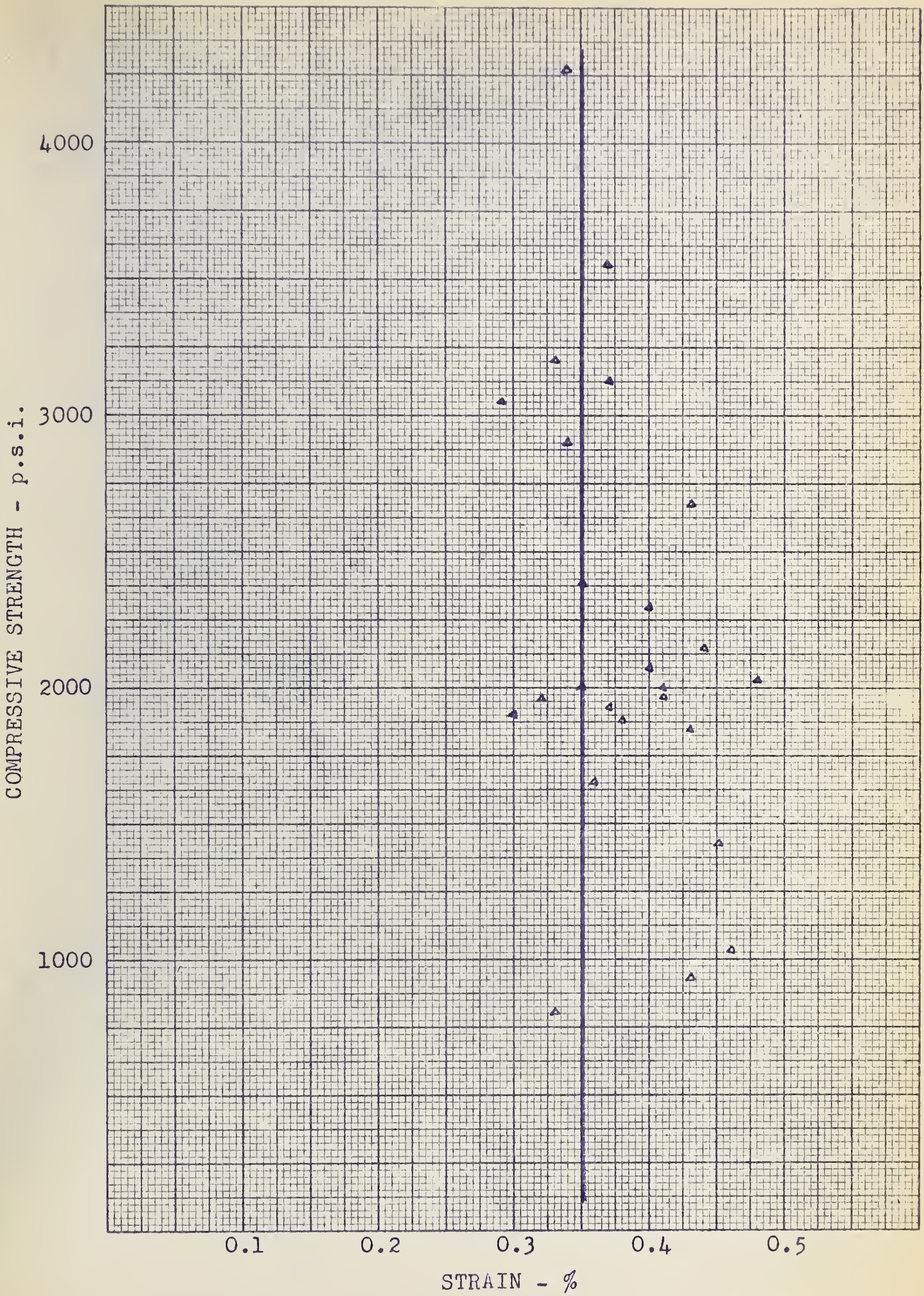
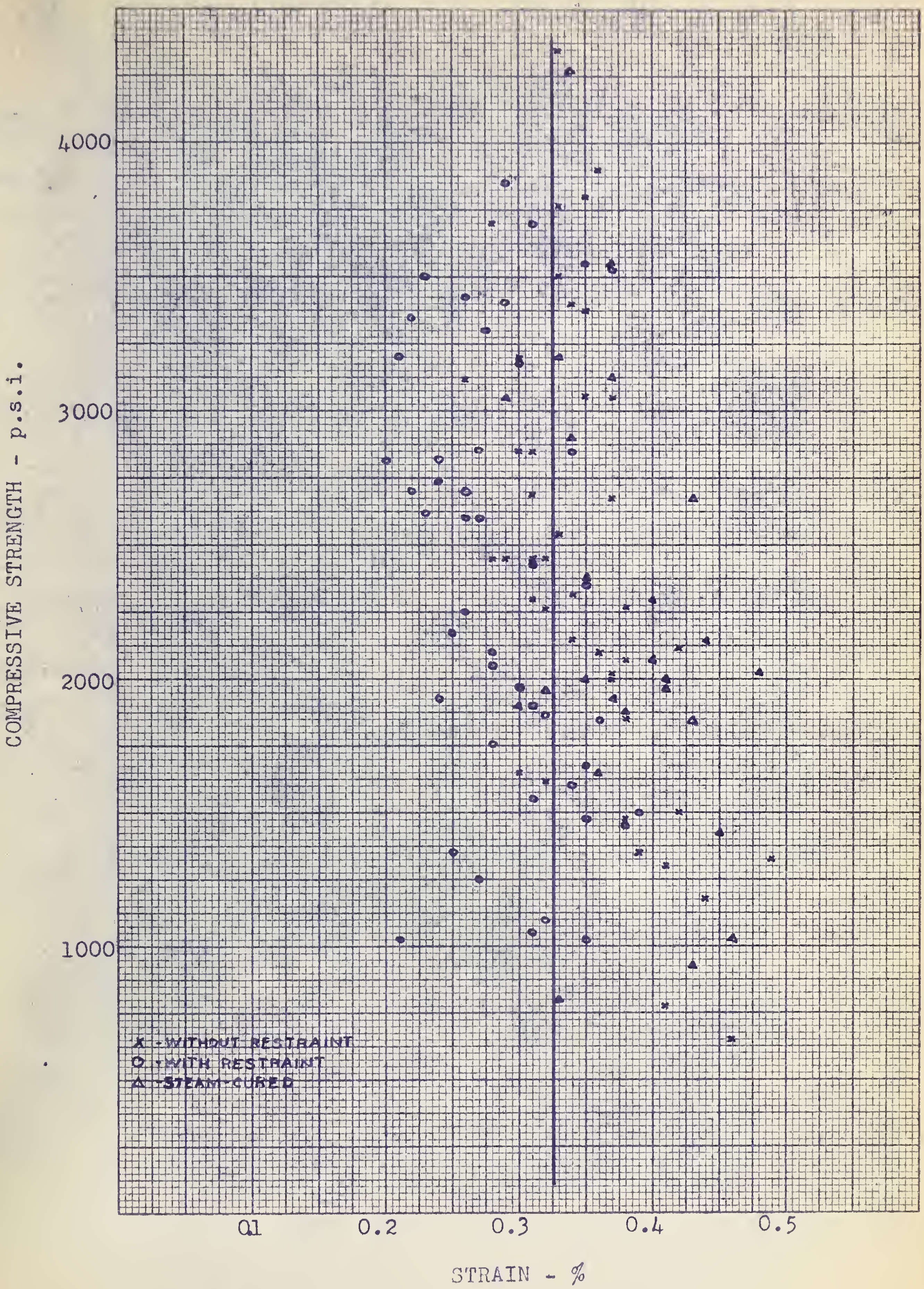


FIGURE 30

LIMITING STRAIN AT 0.85 f'c



Chapter 6

Comparisons with Published Data

There is a lack of published experimental data in the field of plastic flow of concrete in general, and lightweight concrete in particular. All published stress-strain curves for the entire range of strain referred to in this report are for standard sand and gravel concretes.

The first group of these curves was determined in 1938 by O. G. Kiendl and J. A. Maldari, and reported in an article by C. S. Whitney [9]. The six curves illustrated, although characterized by many local irregularities, follow the same general shape of curve determined in this report. The constants are comparable to those expected with standard concrete. For example, a compressive strength stress of 3750 psi., the modulus of elasticity is about 4,200,000 and the limiting strain is about 0.0033 in./in. The modulus of elasticity is greater than corresponding results derived from lightweight tests but the limiting strain is remarkably close.

R. H. Evans[10] plotted four curves using cube

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[9] Whitney, C.S. "Plastic Theory of Reinforced Concrete Design". Am. Society of Civil Engineers Transactions, Vol. 107, 1942, pp. 251.

[10] Evans, R.H. "Plastic Theories for the Ultimate Strength of Reinforced Concrete Beams". Journal Institution of Civil Engineers. Vol. 21, 1943.

strengths of 2500 to 7000 psi. Again he has the same characteristic shape, and for cubes of higher strength, the curves terminate before much plastic flow takes place. Since no mention is made of a restraining device, it is assumed these tests were made without any attempt to account for the elastic energy in the testing machine. Evans erroneously concluded from these curves that higher strength concretes are more brittle. Because his compression strengths are for cubes, exact comparisons are difficult, but the strains shown are in the same order of magnitude.

E. Hognestad[11] although he did not directly test concrete cylinders, plotted the modulus of elasticity and limiting strain against the compressive stress for standard concrete (see figures 31 and 33). The modulus of elasticity for the lightweight concrete determined in this investigation is almost exactly half that reported by Hognestad for standard concrete. He reports the limiting strain as a constant equal to 0.0038 in./in., but this value is based on an idealized stress-strain curve that has as its ultimate load a value only 85% of that determined by tests and a further reduction of load carrying capacity of 85%. This

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11 Hognestad, E. "A Study of Combined Bending and Axial Load in Reinforced Concrete Members". U. of Illinois, Bulletin 399.

would correspond to the strain at 72.3% of the ultimate stress in this report. When the limiting strain for lightweight is based on this figure, agreement is very close.

The best comparison with published data is provided by an account of a series of tests conducted by the U. S. Bureau of Reclamation[12]. In this report some eighteen curves are presented, all tested with the same restraining device that was used for tests in group (2). However, in the original paper these stress-strain curves were not analysed, for either the modulus of elasticity or the limiting strain. For comparative purposes these curves were analysed in the same fashion as were the curves of this testing programme, and the results obtained are shown in figures 32 and 34. Briefly, they are

$$E_c = 1,300,000 + 554\ f'c$$

$$e_L = 0.00315 \text{ in./in.}$$

This limiting strain is seen to be in excellent agreement with results determined for lightweight. Although the modulus of elasticity is lower than that determined by Hognestad for compressive strengths below 5300 psi., it is again considerably greater than any of the values determined

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12 Ramaley D. and McHenry D. "Stress-Strain Curves for Concrete Strained beyond the Ultimate Load." Lab. Report SP-12, U. S. Bureau of Reclamation.

in this investigation.

More curves at other strengths are required before definite conclusions regarding the modulus of elasticity can be drawn from the work of Ramaley and McHenry.

The tests reported in this thesis are more complete for a wider range of variables than any other report found in establishing the value of these two constants (E_c and e_L) in terms of the compressive strength. The consistency of results obtained equals or exceeds the consistency of results obtained by the above investigators named. The per cent variation for limiting strain is less than that shown by Hognestad for this value.

Again it is stressed that published data regarding the modulus of elasticity and limiting strain in terms of the compressive strength, particularly for lightweight concrete, is almost completely non-existent and thus no direct comparisons could be made. However, on the basis of this investigation, it may be stated that the modulus of elasticity for lightweight is approximately one-half that for standard concrete and the limiting strain is constant to both, regardless of the type of cure employed.

FIGURE 31

MODULUS OF ELASTICITY

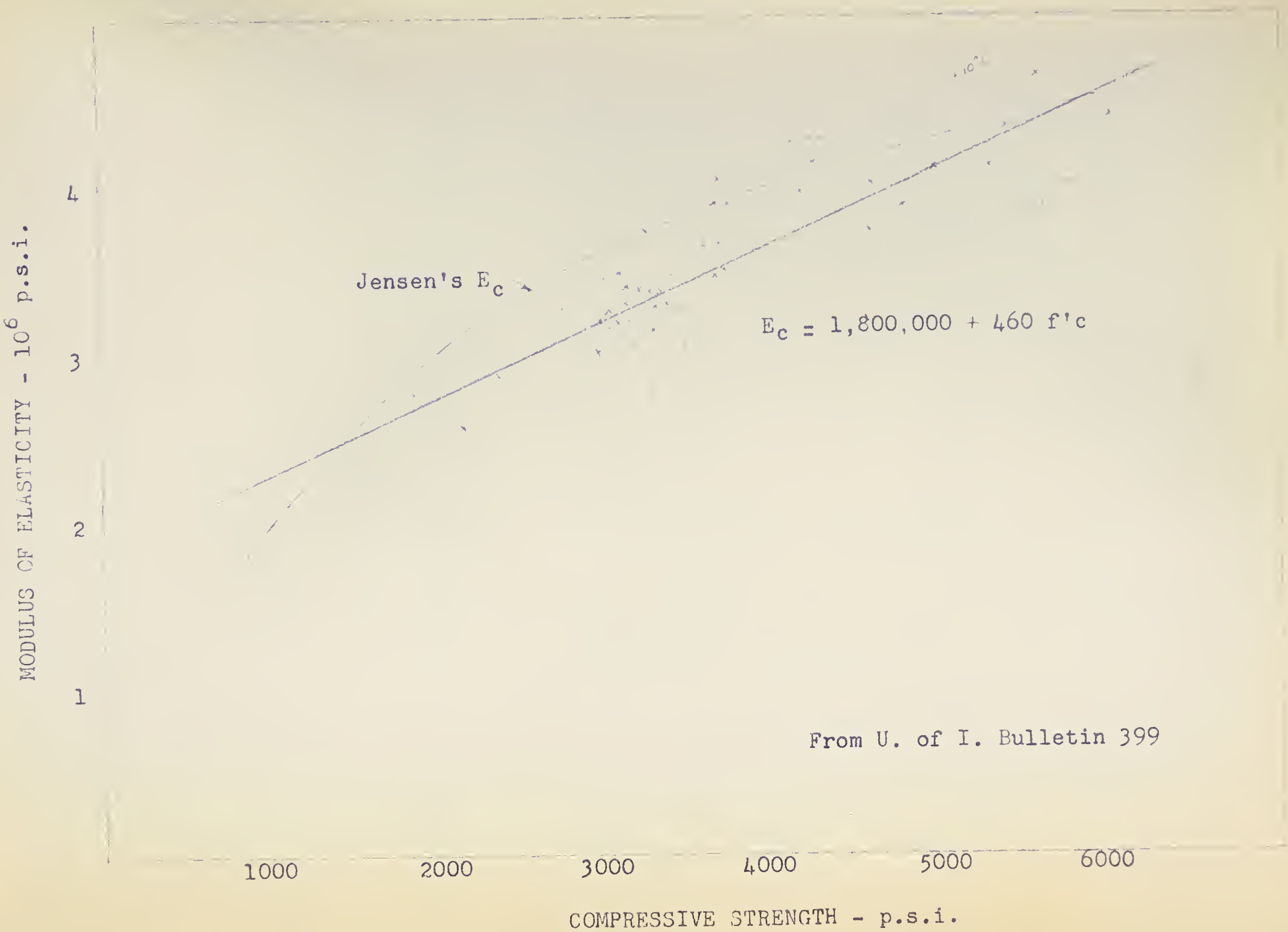
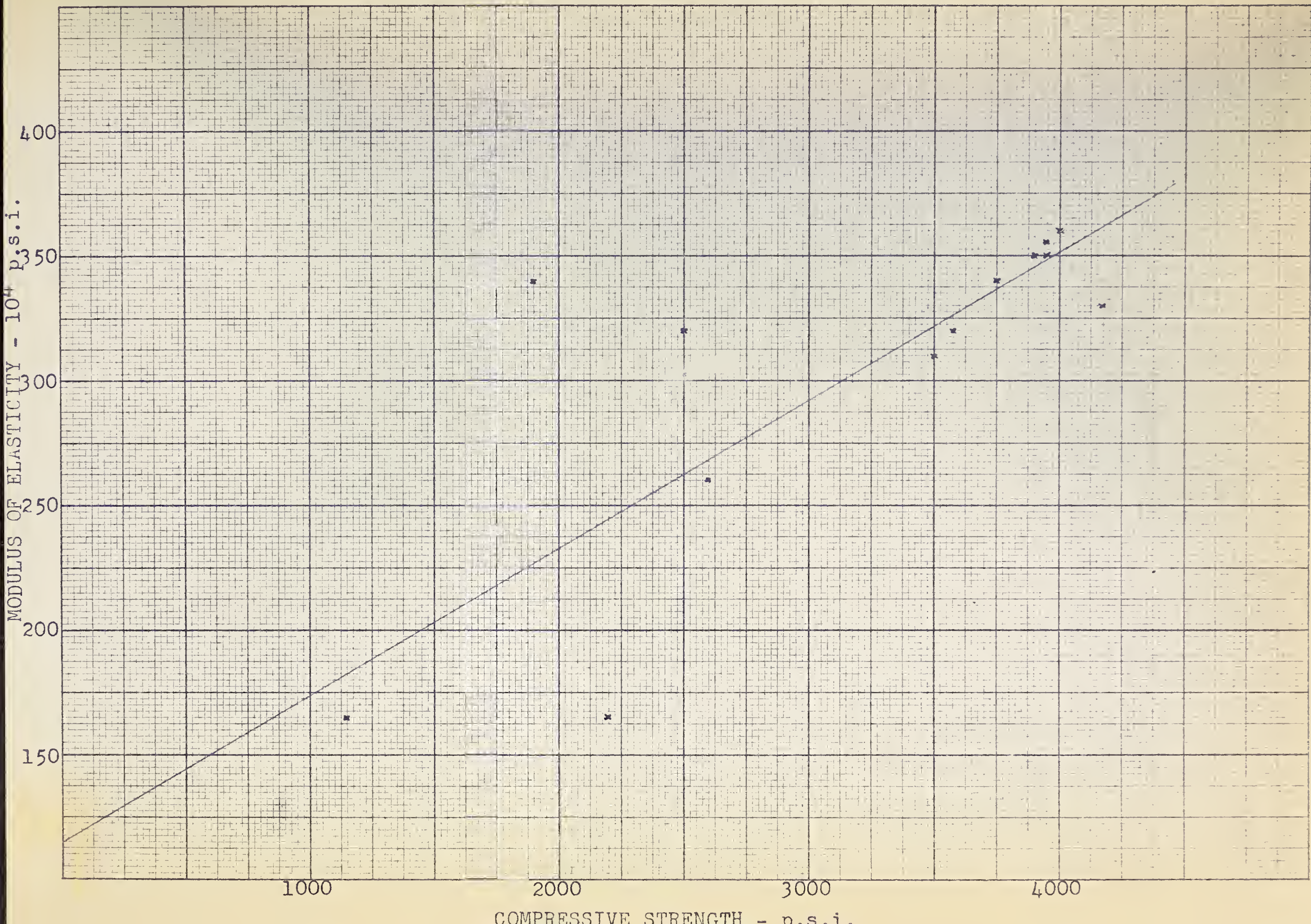


FIGURE 32

MODULUS OF ELASTICITY - RAMALEY AND MCHENRY



LIMITING STRAIN

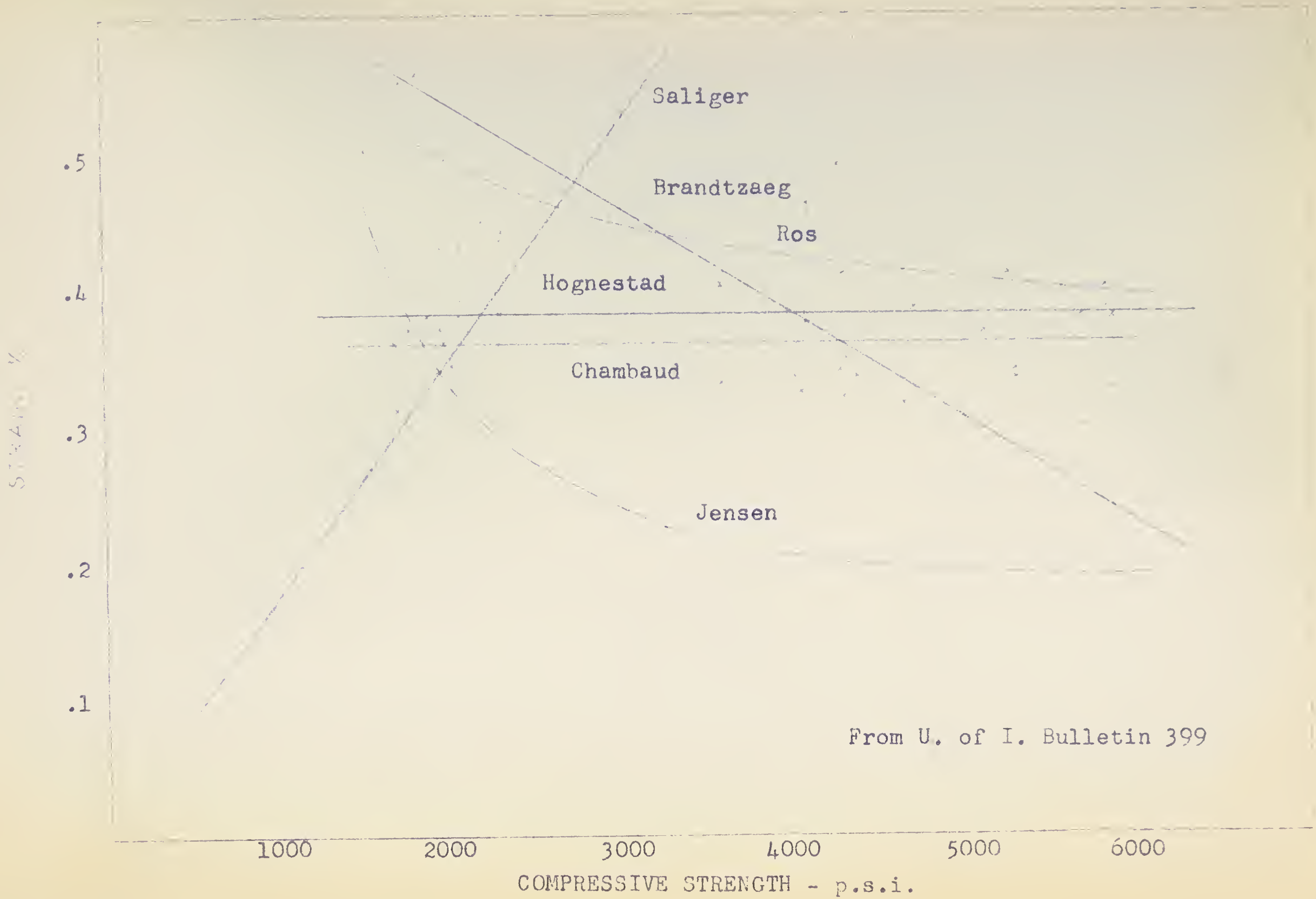
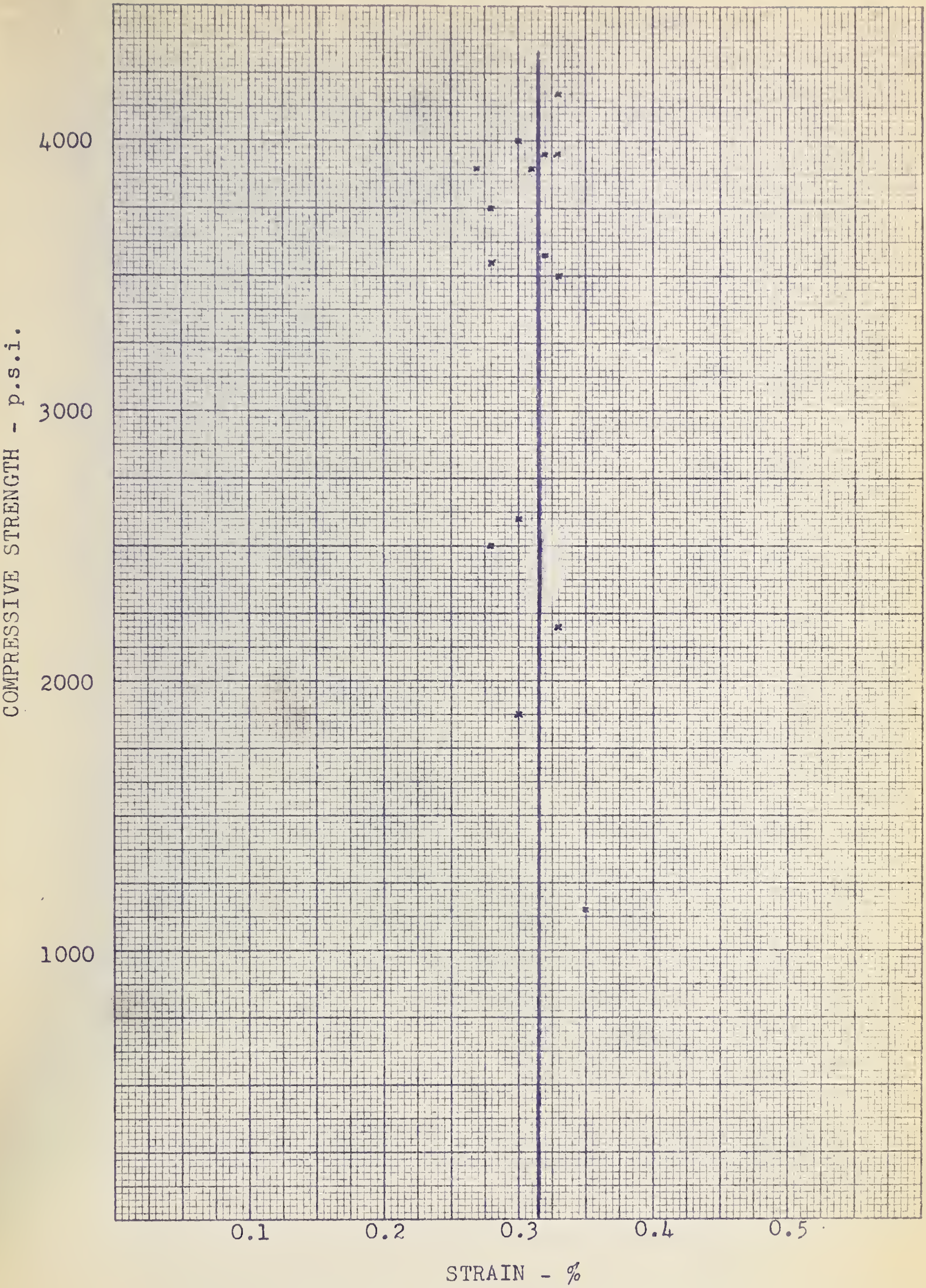


FIGURE 34

LIMITING STRAIN - RAMALEY AND MCHENRY



Chapter 7

Summary, Conclusions and Recommendations

1. Concrete strengths up to 5000 psi. are readily obtained with lightweight aggregates using the design recommendations for standard sand and gravel mixes, providing the aggregate is pre-soaked.

2. Concrete is not intrinsically a brittle material and can be made to flow plastically if subjected to stresses of sufficient magnitude, and still carry load.

3. No appreciable change was noted in either the modulus of elasticity or the limiting strain when loaded with or without the restraining springs. Similarly, there does not appear to be a form factor for larger cylinders if they are in similar proportion.

4. Air-curing for part of the curing time has no marked effect, although higher strengths were noticed in many instances, particularly with the lower strengths. This agrees with the findings reported by Hognestad [13].

5. Although steam-curing gave a higher initial strength, the strength at 28 days was not appreciably influenced. It was impossible from the tests, due to the fact that most cylinders were broken at 28 days and had

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[13] Hognestad E. "A Study of Combined Bending and Axial Load in Reinforced Concrete Members". U. of Illinois, Bulletin 399.

different forms of curing, to plot a reliable strength vs. time curve, which would give a better indication of the effect of steam-cure on strength.

6. The limiting strain for both lightweight and standard concretes is constant when based on 85% of the ultimate compressive strength and is about 0.0033 in./in. Beyond this strain the cylinder is still capable of supporting load but the effect of the shape and arrangement of the aggregate particles, development of shear planes, etc., makes use of this range impractical.

7. The modulus of elasticity is based on the slope of the secant at 45% of the ultimate compressive strength. For this lightweight concrete, it can be approximated closely in terms of the compressive strength, for values of this strength greater than 2000 psi., by the linear relationship:

$$E_c = 900{,}000 + 230\ f'c$$

On the basis of this investigation, the modulus of elasticity can be expressed for the complete range of compressive strengths (0 to 5000 psi.) by the equation:

$$f'c = 1.19 \times 10^{-9} (E_c)^2 - 1.19 \times 10^{-4} E_c$$
$$= 1.19 \times 10^{-4} E_c (10^{-5} E_c - 1)$$

8. For compressive strengths above 3000 psi. lightweight concrete cylinders tested in compression tend to fail by vertical cracking rather than by shear.

In retrospect the following recommendations are made to anyone continuing or duplicating this programme:

1. The restraining springs used in group (2) tests were not considered satisfactory for best results, particularly with lightweight concrete. It is recommended that another device be developed to remove the effects of the elastic energy of the testing machine.

2. A more comprehensive study of the effects of steam-curing on the strength and the modulus of elasticity should be made. Particularly, effects of time for a given type of cure may yield results of some interest. The temperature of the water bath and the length of time the specimen is immersed could also be varied.

3. Although mixes with the desired strength and reasonable workability could be obtained by the method used in this investigation, it is felt that proportioning the aggregate differently may render better results. The mixes tended to be over-sanded, particularly at higher strengths.

It is interesting to speculate on the effect of a reduced modulus of elasticity on design procedures. Using the standard elastic analysis the modular ratio "n" is increased, which means, theoretically, an increase in the resisting moment of the concrete for the same dimensions. However, it should be noted that the limiting strain is similar and it may be possible for compressive failures to occur if the critical percentage of reinforcement is not

watched closely.

A comprehensive discussion on the effects of these results to ultimate theories and the proper evaluation of factors of safety of structural members is beyond the scope of this thesis. However, it does stress the need for more knowledge and understanding before plastic design with lightweight aggregate concrete can be considered for general use. Certainly research in this field is not exhausted.

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APPENDIX 1

MIX DESIGN

APPENDIX 1

The following mix is designed in detail to illustrate the procedure using the following tables:

Conditions

Compressive Strength 2500 psi.

Slump 3 inches.

Maximum size of coarse aggregate 3/4 inches.

Finess modulus of fine aggregate 2.44.

Design

(1) From table 5, the water cement ratio required to produce a strength of 2500 psi. of non-air-entrained concrete is found to be about 6.2 gallons per bag.

(2) The approximate amount of mixing water to produce a 3" slump with 3/4" maximum size aggregate is found from table 3 to be 34.2 gallons of water per cubic yard.

(3) From (2) and (3) the required cement content is computed to be $\frac{34.2}{6.2} = 5.52$ bags per cubic yard.

(4) From table 6 the quantity of coarse aggregate required for a 3/4 inch maximum size of coarse aggregate and a finess modulus of 2.44 for the fine aggregate, is 65% by volume. Considering the aggregate in the bin-dry condition, and splitting this size fraction into 60% for

coarse and 40% for intermediate, a total of

27 x 0.65 x 42.4 x 0.60 = 460 lbs. per cu. yd. of coarse and

27 x 0.65 x 46.8 x 0.40 = 315 lbs. per cu. yd. of intermediate

is required.

(5) To determine the quantity of fines required the solid volume of the known materials is computed.

Solid volume of cement $\frac{5.52 \times 87.5}{3.13 \times 62.4} = 2.48$ cu. ft.

Volume of water $\frac{342}{62.4} = 5.48$ cu. ft.

Solid volume of coarse agg. $\frac{460}{1.13 \times 62.4} = 6.50$ cu. ft.

Solid volume of intermediate $\frac{315}{1.24 \times 62.4} = 4.08$ cu. ft.

Total 18.54 cu. ft.

Solid volume of fines is 27.00 - 18.54 = 8.46 cu. ft.

Weight of fines is 1.94 x 62.4 x 8.46 = 1040 lbs.

Summary of estimated quantities per cubic yard.

Cement	(5.52 bags)	480 lbs.
*Water	(34.2 gals.)	342 lbs.
Fines	(bin-dry basis)	1040 lbs.
Intermediate	(bin-dry basis)	315 lbs.
Coarse	(bin-dry basis)	460 lbs.

* This amount is the mix water required for slump and does not include water absorbed by the aggregate.

Excerpt from A.C.I. Standards 1954

TABLE 1 - Recommended Slumps for Various Types of Construction*

	Slump, in.+	
	Maximum	Minimum
Reinforced foundation walls and footings	5	2
Plain footings, caissons, and substructure walls	4	1
Slabs, beams, and reinforced walls	6	3
Building columns	6	3
Pavements	3	2
Heavy mass construction	3	1

*Adapted from Table 4 of the 1940 Joint Committee Report on Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete.

+When high-frequency vibrators are used, the values given should be reduced about one-third.

TABLE 2 - Maximum Sizes of Aggregate Recommended for Various Types of Construction

Minimum dimension of sections, in.	Maximum size of aggregate,* in.			
	Reinforced walls, beams & columns	Un-reinforced walls	Heavily reinforced slabs	Lightly reinforced or unreinforced slabs
2-1/2 - 5	1/2 - 3/4	3/4	3/4 - 1	3/4 - 1-1/2
6 - 11	3/4 - 1-1/2	1-1/2	1-1/2	1-1/2 - 3
12 - 29	1-1/2 - 3	3	1-1/2 - 3	3
30 or more	1-1/2 - 3	6	1-1/2 - 3	3 - 6

*Based on square openings.

Excerpt from Journal of the American
Concrete Institute, October 1953.

TABLE 3 - Approximate Mixing Water Requirements for Different Slumps and Maximum Sizes of Aggregates[x]

Slump, in.	*Water, lb. per cu. yd. of concrete for indicated maximum sizes of aggregate							
	3/8 in.	½ in.	¾ in.	1 in.	1½ in.	2 in.	3 in.	6 in.
Non-air-entrained concrete								
1 to 2	350	333	308	300	275	258	242	208
3 to 4	383	366	342	325	300	283	266	233
6 to 7	408	383	358	342	316	300	283	250
pproximate amount of entrapped air in non-air-ntrained concrete, percent	3	2.5	2	1.5	1	0.5	0.3	0.2
Air-entrained concrete								
1 to 2	308	300	275	258	242	225	208	183
3 to 4	342	325	300	283	266	250	233	200
6 to 7	358	342	316	300	283	266	250	216
ecommended average total ir content, percent	8	7	6	5	4.5	4	3.5	3

'hese quantities of mixing water are for use in computing cement factors for trial atches. They are maxima for reasonably well-shaped angular coarse aggregates graded ithin limits of accepted specifications.

f more water is required than shown, the cement factor, estimated from these quantities, hould be increased to maintain desired water-cement ratio, except as otherwise indicated y laboratory tests for strength.

f less water is required than shown, the cement factor, estimated from these quantities, hould not be decreased except as indicated by laboratory tests for strength.

Canadian Units

Excerpt from Journal of the American
Concrete Institute, October 1953.

TABLE 4 - Maximum permissible Water-Cement Ratios (Gal. per Bag) for Different Types of Structures and Degrees of Exposure (Canadian Units)

Type of Structure	Exposure Conditions[x]					
	Severe wide range in temperature, or frequent alterations of freezing and thawing (air-entrained concrete only)			Mild temperature rarely below freezing, or rainy, or arid.		
	In air	At the water line or within the range of fluctuating water level or spray		In air	At the water line or within the range of fluctuating water level or spray	
		In fresh water	In sea water or in contact with sulfates[z]		In fresh water	In sea water or in contact with sulfates[z]
'hin sections, such as railings, curbs, sills, ledges, rnamental or architectural oncrete, reinforced piles, ipe, and all sections with ess than 1 in. concrete over over reinforcing	4-1/4	3-7/8	3-1/2[1]	4-2/3	4-1/4	3-1/2[1]
oderate sections, such as etaining walls, abutments, iers, girders, beams	4-2/3	4-1/4	3-7/8[1]	†	4-2/3	3-7/8[1]
xterior portions of heavy nass) sections	5	4-1/4	3-7/8[1]	†	4-2/3	3-7/8[1]
oncrete deposited by tremie nder water	--	3-7/8	3-7/8	--	3-7/8	3-7/8
oncrete slabs laid on the round	4-2/3	--	--	†	--	--
oncrete protected from the eather, interiors of buildngs, concrete below ground	†	--	--	†	--	--
oncrete which will later be otected by enclosure or ckfill but which may be exsed to freezing and thawing r several years before such otection is offered	4-2/3	--	--	†	--	--

[x] ir-entrained concrete should be used under all conditions involving severe exposure nd may be used under mild exposure conditions to improve workability of the mixture.

[z] oil or ground water containing sulfate concentrations of more than 0.2 percent.

[1] hen sulfate resisting cement is used, maximum water-cement ratio may be increased by .5 gal. per bag.

† ater-cement ratio should be selected on basis of strength and workability requirements.

Excerpt from Journal of the American
Concrete Institute, October 1953.

TABLE 5 - Compressive Strength of Concrete for Various Water-Cement Ratios*

Water-cement ratio, gal. per bag of cement (Canadian Units)	Probable Compressive Strength at 28 days, psi	
	Non-air-entrained concrete	Air-entrained concrete
3.1	6000	4800
3.88	5000	4000
4.65	4000	3200
5.43	3200	2600
6.2	2500	2000
7	2000	1600

These average strengths are for concretes containing not more than the percentages of entrained and/or entrapped air shown in Table 3. For a constant water-cement ratio, the strength of the concrete is reduced as the air content is increased. For air contents higher than those listed in Table 3, the strengths will be proportionally less than those listed in this table.

Strengths are based on 6 x 12 in. cylinders moist-cured under standard conditions for 28 days. See Standard Method for Making and Curing Concrete Compression and Flexure Test Specimens in the Field (ASTM Designation C 31).

TABLE 6 - Volumes of Coarse Aggregate per Unit of Volume of Concrete[z]

Maximum size of aggregate, in.	Volume of dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of sand			
	2.40	2.60	2.80	3.00
3/8	0.46	0.44	0.42	0.40
1/2	0.55	0.53	0.51	0.49
3/4	0.65	0.63	0.61	0.59
1	0.70	0.68	0.66	0.64
1 1/2	0.76	0.74	0.72	0.70
2	0.79	0.77	0.75	0.73
3	0.84	0.82	0.80	0.78
6	0.90	0.88	0.86	0.84

[z]Volumes are based on aggregates in dry-rodded condition as described in Standard Method of Test for Unit Weight of Aggregate (ASTM Designation C29).

These volumes are selected from empirical relationships to produce concrete with a degree of workability suitable for usual reinforced construction. For less workable concrete such as required for concrete pavement construction they may be increased about 10 percent.